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Electric Grid Decarbonization Pathways: Landscape Impacts, Policy Interactions, and the Need for Cooperation

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ELECTRIC GRID DECARBONIZATION PATHWAYS: LANDSCAPE IMPACTS, POLICY INTERACTIONS, AND THE NEED FOR COOPERATION

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Abstract

Climate change has motivated governments around the world to ratify aggressive greenhouse gas emissions reduction targets. Meeting these targets will require improved energy efficiency, behavior changes, and energy system decarbonization. Many climate change and energy policy targets imply the deployment of large amounts of low carbon, renewable energy resources like wind turbines and solar photovoltaic (PV) panels but do not specify how these resources will be sited on the landscape. The relationships between weather conditions, terrain, land cover, existing electric grid infrastructure, and electricity consumers will govern how these wind and solar PV infrastructure configurations develop and how quickly they will be implemented.

This dissertation develops methods for modeling policy goal-compliant wind and solar PV infrastructure configurations and their land use requirements, extends these methods to explicitly account for the resulting land use/land cover change patterns, and concludes with a macro-scale discussion of energy system geographies and their co-evolution with the societies that rely upon them in a decarbonized electric grid future. Chapters 2 and 3 each feature a case study of Vermont and its ambitious energy and emissions-related goals. We find that Vermont can meet many of these goals with less than 1% of its land area occupied by wind and solar PV infrastructure using a wide variety of infrastructure ratios and siting strategies. Chapter 4 views energy systems through the proposed 'energyshed' lens. We define energysheds as the geographic area over which energy is produced, refined, transported, stored, distributed, and consumed. We argue that energy system decarbonization offers opportunities to democratize and decentralize energy systems physically and administratively and that the spatial relationships between energy system infrastructure, ownership, and energy consumers will dictate the trajectory of the electric grid decarbonization process.

Dedication

This dissertation is dedicated to my wonderful parents, Jean and Chris Thomas,
and was written in solidarity with the scientists, public servants,
and citizens of the world fighting to combat climate change.

In memory of my uncle, Professor Paul A. Thomas, University of Georgia.

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Chapter 1: Introduction

Anthropogenic climate change, driven primarily by the consumption of fossil fuels for energy production, deforestation, and agricultural practices, has resulted in approximately 0.8°C of global average surface temperature warming relative to the early 19th century (Pachauri et al., 2015). Impacts of this initial warming of the Earth's atmosphere are already being felt by human populations, ecosystems, and natural geophysical processes alike. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a special report titled *Global Warming of 1.5°C* which declared that "[p]athways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems" (Intergovernmental Panel on Climate Change, 2018). Implementing the "rapid and far-reaching transitions" called for by the IPCC will require the collective efforts of every segment of society from national governments to businesses to individuals. These efforts ultimately fall into one of two categories: changing energy demand habits and changing the energy sources used to meet energy demand.

In the context of climate change, reduction of overall energy demand is desired, particularly while greenhouse gas (GHG) intensive fossil fuels meet three-quarters of energy consumption needs (International Energy Agency, 2018). This can be accomplished either through improved energy efficiency (using less energy to achieve the same service) or through behavior change. Since energy consumption underpins so many aspects of modern life, there are countless ways that behaviors or preference changes can influence energy consumption habits. The environmental ramifications of our energy consumption are then determined by the types of energy we use and how we access those energy sources. This dissertation addresses the second category with a focus on fuel-switching in the electricity system, the ramifications of electricity system decarbonization for society, and the influence that society has on the trajectory of electricity system decarbonization.

There is a growing consensus among policy makers and energy system stakeholders that decarbonizing the electricity system and shifting energy consumption into electricity is the *de facto* climate change mitigation pathway. Evidence of this consensus can be found in the steady adoption of renewable, low carbon electricity sources (particularly wind and solar PV; Zervos and Adib, 2018) and the growing number of governments ratifying statutory energy goals (SEGs) that mandate the adoption of non-fossil fuel energy sources (Atlanta, Georgia City Council, 2017; European Union, 2009; United Nations Framework Convention on Climate Change, 2015). The exact contents of these laws vary widely but most include specific targets for the adoption of renewable energy[1] to meet electricity demand. The state of Vermont, for example, aims to meet 90% of the state's total energy needs with renewable energy sources and reduce the state's total GHG emissions to 95% below 1990 levels by the year 2050 (Vermont Department of Public Service, 2016).

The deployment of one type of energy infrastructure over another (along with the location, ownership, and financing of these infrastructure developments) is usually determined[2] by a wide range of stakeholders and their respective priorities. Most of these stakeholders are non-governmental; examples include energy developers, businesses, landowners, landlords, and individual citizens. While SEG-ratifying

[1] It is important to note that "renewable energy" is not equivalent to "low-carbon" or "carbonless" energy.

[2] Setting aside command-and-control economic systems in nations like North Korea and, to a lesser extent, Cuba, China, or the former Soviet Union.

governments can typically assert some control over these decision-making processes through regulation, technology prohibitions, and financial incentives, the bulk of the decision-making is handled by these non-governmental stakeholders. This will require compromise and consent among all electricity system stakeholders, each of whom controls different amounts of decision-making power, financial resources, technical expertise, and personal priorities within and adjacent to the electricity system. Given the rapidly approaching time horizons for climate change tipping points, development and implementation of a consensus decarbonization pathway is urgently needed. At present, no such pathway exists. Setting aside climate change denial and opposition, there are myriad reasons for the slow, irregular adoption of low carbon energy sources in both developed and developing countries. Many of these reasons share a common root: discrepancies between who bears the burden for implementing a low-carbon energy system and who receives the benefits. In turn, many of these discrepancies are driven by spatial relationships.

Contemporary energy systems already explicitly and implicitly link people, energy sources, infrastructure, money, land, and ecosystems in space. Crude oil deposits, for example, are not uniformly distributed on Earth nor are the people and machines that utilize their energy. The negative externalities associated with oil and gas extraction, processing, and transportation can be substantial (e.g. Mendelssohn et al., 2012; McKenzie et al., 2016; McKenzie et al., 2017; Whitworth et al., 2017; Czolowski et al., 2017). This motivates the separation of energy consumers from the ramifications of the systems and processes that presently supply their energy whenever it is possible to do so. For example, New England does currently not host any oil, natural gas, and coal extraction and refining facilities. Well over half[3] of all energy consumed in

[3] 1,918.4 trillion BTUs of a total of 3,150.3 trillion BTUs in 2016. This is an underestimate of total fossil fuel consumption as fossil fuels used for electricity generation are not listed separately in the EIA source data.

New England each year is provided by fossil fuels imported from outside the region meaning that the negative externalities associated with this consumption are borne elsewhere, out of sight and out of mind (US Energy Information Agency, 2018).

Future low carbon energy systems will address many of the negative externalities of fossil fuel-based systems, but new negative externalities will take their place. Resistance to decarbonization efforts often indirectly points to the spatial reallocation of the negative externalities associated with energy production. For example, the construction of wind turbines on a nearby ridgeline or in near-shore waters often triggers stiff opposition from local residents who oppose the visual or auditory disruption that wind turbines create. Just as fossil fuel extraction activities are tied to specific locations based on resource availability, low carbon energy sources are dependent on natural resources that are irregularly distributed in space and time. Wind speeds vary widely with location, elevation, terrain complexity, and season (James et al., 2017). Sunlight availability varies with time on daily and annual cycles with respect to local weather conditions and Earth's position relative to the Sun. Hydropower, tidal power, biomass, and geothermal energy resources all follow suit. Transitioning away from fossil fuels to low carbon energy sources will not absolve us of the conflicts between energy production impacts and energy consumption benefits, it will simply redistribute them in space. Ultimately, it is the locations of human populations, energy resources, infrastructures, atmospheric conditions, landscapes, and political and economic power that drive the creation and evolution of energy systems. Any approach to modifying energy systems that does not recognize this reality and its ramifications is bound to perpetuate the inequities and imbalances characteristic of contemporary energy systems, become bogged down in negotiations and disputes, or fail altogether.

This dissertation develops methods for translating SEGs into real-world wind and solar PV infrastructure configurations and assessing the landscape impacts of these configurations. The resulting pathway options are designed to convert the implied infrastructure requirements contained in SEGs into tangible, actionable pathway options for stakeholders to review, debate, and ultimately implement. This dissertation also considers how low carbon energy system transitions could be more effectively managed if they work with, rather than against, the spatial relationships and tensions that undergird contemporary energy systems. It is the focus on and integration of these relationships which set this work apart from other contemporary energy system modeling approaches. The remainder of this introductory chapter provides a brief overview of the scholarly context in which this work was conducted. Each of the second, third, and fourth chapters contains a more focused background section for its respective contents.

1.1 Energy System Transitions

The quantitative and qualitative discussions of energy systems in this dissertation are primarily rooted in the sociotechnical transitions literature. F. W. Geels defines sociotechnical systems in his 2005 paper as “consist[ing] of a cluster of elements, including technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks and supply networks” that, in combination, fulfill societal functions and meet societal needs (Geels, 2005). Transitions between sociotechnical systems have occurred many times throughout human history and frequently symbolize their particular eras (e.g. Bronze Age, Iron Age, etc.). Energy system transitions (ESTs) are a prominent subset of the wider sociotechnical transitions literature, particularly because energy underpins so many other aspects of life. ESTs also often enable or amplify transitions in other sociotechnical systems.

Geels' multi-level perspective (MLP) on sociotechnical transitions is a powerful tool for examining the dynamics at play in ESTs. Energy system decarbonization efforts are currently underway in many developed nations fit the MLP framework well. The landscape level trends in this case are the threats to planetary and human well-being from climate change and the growing governmental energy policy response to climate change. The technical niches can be seen in the development and initial growth of various renewable energy technologies (e.g. wind turbines, solar PV panels, wave and tidal power, etc.), electric vehicles, battery storage technologies and novel battery chemistries, domestic energy management devices (e.g. 'intelligent' home temperature controls, in-home energy consumption monitoring devices, internet-enabled appliances, etc.), and other as-of-yet unknown ideas in development around the world. Some technologies, such as hydroelectric power, geothermal power, and biofuels already feature in contemporary energy systems but may behave in an MLP context more as a niche technology due to resource availability or initial financial disadvantages relative to incumbent fossil fuels. The combined pressures of worsening climate change and growing consensus on governmental energy policies at the landscape level, and increasingly successful niche energy sector technologies are beginning to seep into the middle "sociotechnical regime" tier. It is this tier where most of the rest of society is found, including businesses, banks, academia, and individual citizens. The interactions of these entities generally, and electricity system stakeholders specifically, will determine the speed at which low-carbon energy sources are implemented. Geels contends that "[t]ransitions are complex processes that cannot be overseen or steered from one viewpoint. They are emergent outcomes of interactions between social groups with myopic views and differing interests, strategies and resources" (Geels, 2005). It is the gradual, uneven modification of "normal" conditions in the sociotechnical regime, due to the decisions and interactions of its constituent individuals and firms, that shapes the final outcome of the EST.

Key attributes of successful (i.e. completed) ESTs include the following:

- Energy end-use cases dictate the course of an EST and a wide variety of societal factors internal and external to energy systems can influence these end-use cases (Grubler, 2012)
- New energy sources must provide the same or better energy services as the previous incumbent energy source for lower prices (Bashmakov, 2007; Fouquet, 2010)
- ESTs tend to occur gradually over time, with periods of faster and slower change throughout (Grubler, 2012)
- Institutional support (i.e. consent, with or without advocacy) is necessary, but not sufficient (Grubler, 2012; Solomon & Krishna, 2011)

In light of these lessons from past ESTs, the decarbonization of the electricity system faces a number of challenges. First, the long time scales (decades to centuries) of many past ESTs do not inspire confidence that effective climate change mitigation can be achieved through a hands-off approach. Second, ESTs that featured heavy-handed or deliberate governmental and institutional interventions have been variously successful and often feature curtailments of citizens' preferences, freedom of political dissidence, and decision-making powers (Solomon & Krishna, 2011). Third, if new energy sources like wind and solar PV cannot offer additional energy services (aside from greenhouse gas emission reductions) to the end user and/or lower energy prices, they are unlikely to supplant incumbent energy sources and systems on their own (Fouquet, 2010). For electric grid decarbonization (and the low carbon EST more broadly) to succeed, swift concerted actions must be taken by stakeholders to alleviate these challenges. The next section provides an overview of the contemporary electric grid in the United States, including how it functions, its physical and organizational structure, its stakeholders, and their roles within the electric grid.

1.2 The Contemporary Electric Grid in the United States

Electricity represented an estimated 22.3% of worldwide energy consumption in 2016 with fossil fuels meeting 65.3% of that demand (International Energy Agency, 2018). While total worldwide energy consumption doubled between 1973 and 2016, worldwide electricity consumption increased four-fold due to the growth of computing technologies and the expansion of access to electricity in developing nations (International Energy Agency, 2017, 2018). With 1.1 billion people still without electricity access worldwide and continued population growth, electric grids will be under increasing pressure even without the added burden of climate change (International Energy Agency, 2017). The addition of climate change to the list of challenges facing electric grid operators and stakeholders only compounds existing pressures to meet electricity demand safely, reliably, and cheaply.

The conventional electric grid structure features a one-way flow of electricity from generators to consumers via a highly interconnected system of wires and control devices. Electric grids in North America span thousands of miles and connect tens of millions of customers with electricity generators spread throughout the continent. The electric grid is jointly administered by regional transmission organizations (RTOs) and independent system operators (ISOs), electricity generators, and distribution utilities (DUs). RTOs and ISOs continuously coordinate the matching of electricity demand (represented by DUs) to supply (provided by generators), monitor system safety, and act to restore electricity service during system disruptions or failures. DUs draw power from the high-voltage transmission lines of the grid, distribute it directly to consumers, maintain the distribution lines and associated equipment, and collect customer payments.

A number of disruptive forces have arrived in the electricity sector in developed nations in recent years, particularly the rapid growth of distributed energy resources (electric vehicles, energy storage, rooftop solar PV, and so on) and intermittent electricity generation sources (primarily wind and solar PV, but also hydroelectric power in some cases). Distributed energy resources (DERS) and intermittent electricity generation pose new problems for grid operators in a variety of different ways. Energy storage devices, including electric vehicles and purpose-built batteries, can serve both as electricity supply and demand. Other DERs, particularly distributed solar PV generation resources, can provide electricity to partially or fully offset a consumer's electricity demands locally for short periods without energy storage capacity and for extended periods with energy storage capacity. Distributed solar PV generation can also feed energy back "upstream" in the grid in sufficient quantities to both strain local electricity distribution lines and, in aggregate, temporarily reduce electricity demand substantially (Denholm et al., 2015). This latter phenomenon, in conjunction with the large swings in net electricity demand that can occur when solar PV generation rises and falls due to cloud cover or the day/night transitions, are already appearing on electric grids around the world.

These challenges are compounded by the intermittent nature of wind and solar PV electricity generation. Unlike most conventional electricity generation sources, wind and solar PV produce electricity at the whims of the weather rather than at the command of an electric grid operator. Though weather forecasting has advanced considerably in recent years, weather forecasts are not and will never be perfect, making expected wind and solar PV electricity generation at any given time uncontrollable and at least somewhat unreliable (Wang et al., 2016). Grid operators that are tasked with delivering electricity reliably, safely, and cheaply are now expected to maintain the same levels of service while integrating a range of uncontrollable and/or unpredictable electricity sources and sinks (Martinot, 2016). As society looks to low-carbon and carbonless electricity sources as a pathway towards mitigating climate change, our electric grids will not only be responsible for higher and higher proportions of our energy demands but also be asked to meet these demands with fewer and fewer controllable generation sources. Disagreements between electric grid stakeholders on what types of infrastructure should be used, where they should go, who benefits from them, and who pays for them will all stifle implementation of the "rapid and far-reaching transition" that is necessary for climate change mitigation.

1.3 Energy Systems as Spatial Entities

In reshaping our energy systems and behaviors to combat climate change, we will change how we produce our energy and almost certainly *where* the impacts of our energy consumption behaviors are felt. Contemporary global energy systems are enormously complex and encompass large amounts of resources, labor, money, land, and waste products. Each energy source we use, either in an intermediate or final source, carries with it different benefits and drawbacks in each of these categories. For example, the extraction, processing, transportation, and sale of fossil fuels, which make up the majority of energy consumption in America and elsewhere, requires significant amounts of land area (and sea area). In North America alone, 30,000 km^2 of land is used just for oil drilling activities (Allred et al., 2015). But these 30,000 km^2 of land are not contained in one contiguous plot, nor are they representative of the total landscape impacts of the petroleum-based energy system. The land in question is distributed widely over many of states and provinces in the United States and Canada, embedded within other land use types, habitats, human settlements, and protected lands (Allred et al., 2015). Additional land area is required for storing, transporting, refining, and selling the resultant end-use products. The same is true of other energy sources, both carbon-intensive and low-carbon (Fthenakis & Kim, 2009).

Transitioning away from fossil fuels will therefore change, rather than eliminate, the landscape impacts of our energy consumption behaviors and energy systems more broadly (Bridge et al., 2013). Embedded within this transition is not only the change in the total land area footprint of low carbon energy sources relative to fossil fuels but also changes to the distribution of impacted lands. If wind and solar PV infrastructure is widely deployed to reduce greenhouse gas emissions, many people and places that were previously unaffected by the negative externalities of our collective energy consumption behaviors will now be affected. If energy generation is kept far away from consumers, our reliance on the resilience of the grid will become even more entrenched. The more we ignore energy efficiency improvements and energy conservation practices, the more land we will need to use for renewable energy infrastructure. In order to adequately inform stakeholders about the positive and negative impacts of undertaking electricity system decarbonization, landscape impacts resulting from this transition must be assessed, documented, and communicated to stakeholders.

1.4 Summary

The geographical links that bind people, places, and energy are inescapable and we must consider them carefully when charting a course for the future of our energy systems. This principle is the primary through-line that links the three proceeding chapters of this dissertation together. Chapters 2 and 3 develop methods for assessing, documenting, and communicating the physical manifestations of sample policy-compliant energy systems. Chapter 4 provides a conceptual companion to these technical methods with the introduction of the energyshed lens. Energysheds are proposed as a device for assessing how energy systems can be actively reshaped, rather than passively, based on the spatial relationships inherent in energy systems. The fifth and final chapter of this dissertation summarizes and reinforces the connections between Chapters 2, 3, and 4. Chapter 5 then concludes by providing a roadmap for unifying the technical and conceptual findings of this dissertation in support of future research activities and, more importantly, the real-world implementation of low carbon energy transitions at local and regional scales.

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Chapter 2: Constructing statutory energy goal compliant wind and solar PV infrastructure pathways[1]

2.1 Abstract

Concerns over climate change have led governments around the world to establish a range of renewable, low-carbon energy goals. Plans for meeting these targets vary widely in their ambition, specificity, and time horizons. Wind and solar electricity generation will feature prominently in future energy systems that meet these renewable, low-carbon energy goals. Implementing large-scale wind and solar PV infrastructure configurations in a timely fashion will require cooperation between and among electric grid stakeholders and communities that host the infrastructure.

This paper presents methods for constructing a diverse range of wind and solar PV energy infrastructure pathways that meet statutory energy goals, measuring their land area impacts, and assessing their performance relative to electricity demand. A case study on the state of Vermont's statutory energy goals from its 2016 Comprehensive Energy Plan is presented as an example. While total wind and solar PV infrastructure requirements would increase several-fold, Vermont's statutory energy goals can be met while occupying less than 1% of the state's land area. Vermont electricity demand was most effectively met by balanced configurations of wind and solar PV similar to the state's present wind and solar PV resources, while 100% wind or 100% solar PV configurations were less effective.

[1]The contents of this chapter were submitted for publication to *Renewable Energy* on June 13th, 2019 in the following form: Thomas, A.W., Racherla, P.. (2019). Constructing statutory energy goal compliant wind and solar PV infrastructure pathways. *Renewable Energy*.

2.2 Introduction

Climate change, driven by anthropogenic greenhouse gas emissions, has already increased global average surface temperatures by 1.0 °C (Intergovernmental Panel on Climate Change, 2018). The Intergovernmental Panel on Climate Change (IPCC) recently reiterated the need for "rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems" to limit global warming to 1.5 °C and avert the worst impacts of climate change (Intergovernmental Panel on Climate Change, 2018). Renewable, low-carbon energy sources, particularly wind and solar photovoltaic (PV) electricity generation, are increasingly being adopted worldwide both for environmental reasons and because of their increasingly competitive economic positions (Zervos & Adib, 2018). In response to these trends, local, regional, national, and international governments (e.g. Atlanta, Georgia City Council, 2017; Vermont Department of Public Service, 2016; United Nations Framework Convention on Climate Change, 2015) are establishing binding targets for renewable, low-carbon energy production, hereafter referred to as 'statutory energy goals' or SEGs. Many SEGs focus on decarbonizing the electricity system and substituting fossil fuel energy consumption (e.g. transportation, heating, cooking, etc.) for electricity consumption. Achieving these SEGs through "rapid and far-reaching transitions" in the electricity system, among others, is crucial for averting the worst consequences of climate change.

Numerous studies of electricity systems powered by significant proportions of renewable, low-carbon energy sources have been conducted in recent years, covering topics including wind and solar PV generation reliability, electric grid stability and capacity constraints, and economic feasibility (Ackermann et al., 2016; Aghahosseini et al., 2019; Becker et al., 2014; Budischak et al., 2013; Gils et al., 2017; Nelson et al., 2012; Schaber et al., 2012; Tamimi et al., 2013). These studies vary widely in their target wind and solar PV energy penetrations, the quantity and diversity of wind and solar PV infrastructure deployment scenarios tested, and the sophistication of their infrastructure siting methods. Relatively few studies explicitly consider the land area impacts of large-scale wind and solar PV infrastructure deployments and the influence of generation infrastructure siting choices on overall electricity system performance (Arent et al., 2014; Hernandez et al., 2015; Jacobson et al., 2017). We contend that explicitly capturing these geospatial impacts of wind and solar PV electricity generation deployment is vital for understanding how high wind and solar PV-penetration electric grids will be implemented.

Large incumbent electricity generators like coal, natural gas, nuclear, and hydropower generate large quantities of electricity on relatively small, widely separated parcels of land. This dynamic leads to significant land area and related environmental landscape impacts in the few areas that host the generators themselves, leaving most other areas of the landscape essentially unaffected. A future wind and solar PV powered grid will likely draw energy from electricity generation infrastructure that is distributed much more widely across the landscape than incumbent generators thanks to their reliance on prevailing weather conditions for electricity generation and their inherent modularity (Perez and Fthenakis, 2015; Santos-Alamillos et al., 2016). In turn, the infrastructure siting processes that attend electricity system decarbonization driven by wind and solar PV will not only rise sharply in number but will also frequently trigger opposition from those who oppose the landscape disruption that wind and solar PV can cause (Carlisle et al., 2015; Walker et al., 2014). Existing land uses, land protections, and unsuitable terrain like waterways and steep slopes will also constrain wind and solar PV deployment. These phenomena represent significant hurdles to wind and solar PV growth and, if not recognized and dealt with, could greatly hinder the implementation of decarbonized electricity systems mandated by SEGs both in time and in scope. In North America, regional transmission organizations (RTOs) and independent system operators (ISOs) are charged with operating and modernizing the electric grid. RTOs and ISOs are under pressure to both accommodate new wind and solar PV generation capacity and maintain existing grid safety and energy provision reliability standards. If RTOs and ISOs can proactively plan for grid extensions and upgrades to accommodate high penetrations of wind and solar PV generation infrastructure, the chances of SEG achievement and continued grid reliability will increase dramatically. More granular infrastructure siting and landscape impact information can therefore enhance the efficacy of grid planning exercises and contribute significantly to grid decarbonization efforts.

This paper examines how different SEG-compatible wind and solar PV configurations compare on the basis of total generation infrastructure needs, land area requirements, and electricity demand satisfaction. The model used to build SEG-compatible wind and solar PV configurations relies on five years of high spatiotemporal resolution weather data for the contiguous United States (CONUS) to provide granular, high-quality electricity generation estimates. A case study for the American state of Vermont and its SEGs is presented to illustrate how different wind and solar PV infrastructure ratios, siting patterns, and electricity demand levels drive wind and solar PV electricity generation infrastructure needs. By better defining what SEG-compatible wind and solar PV deployments look like and what impacts they have on the landscape, grid integration and planning studies can more readily capture the operational dynamics of highly wind and solar PV dependent electrical systems and reckon with the implementation challenges that will shape real-world, large-scale grid decarbonization. Section 2.3 of this paper describes the datasets and modeling methods used to produce SEG-compatible wind and solar PV infrastructure deployments. Section 2.4 establishes the Vermont case study and section 2.5 contains the results of the case study scenarios. Section 2.6 contains a discussion of the case study findings and context for the enhancement and application of this study. Section 2.7 provides a concluding summary of this paper and suggested areas for proceeding work.

2.3 Methods and Data

The Renewable Energy Growth Scenario (REGS) model described here is an evolution of the model presented in Becker et al. (2014). Our model uses higher spatial resolution wind speed and sunlight data, two types of solar PV panels, and incorporates existing wind and solar PV generation infrastructure. Like Becker et al. (2014), our model covers all of CONUS and allows for discrete modeling of wind and solar PV infrastructure by sub-region. Unlike Becker et al. (2014), our model does not consider offshore wind turbine siting.

2.3.1 Weather data

James et al. (2017) provides hourly irradiance and 80m elevation wind speed data from 2013 to 2017 for the CONUS, southern Canada, and northern Mexico on a 3km by 3km grid. The REGS model uses 43,800 hours of data spanning 0800 UTC 1 January 2013 to 0700 UTC 1 January 2018. 29 February 2016 is omitted to simplify year-to-year comparisons and daylight saving time is ignored. Of the 43,800 hours possible in this date range, the James et al. (2017) data set contains 35,192 hourly files for an availability rate of 80.3%. Gaps in the data were filled by systematically copying available data from equivalent hours in other years to ensure that climatological characteristics and sunlight availability are identical. The James et al. (2017) data set was created using an experimental version of the High Resolution Rapid Refresh numerical weather prediction model. Biases in the wind and solar data are noted in sections 2.3, 2.4, and 5 of James et al. (2017). Wind speed biases in the James et al. (2017) data are modest at approximately 0.5 to 1 m/s higher than observed wind speeds at a test site in Colorado. Sunlight biases are shown to be more variable across CONUS. In New England, where this paper's case study is located, sunlight biases in the James et al. (2017) data set are as much as 0.75 kWh m^{-2} day^{-1} sunnier than observations. See section 2.4.5 for further discussion.

2.3.2 Wind and solar PV power generation

Wind and solar PV electricity generation estimates are calculated using the James et al. (2017) data set and a variety of assumptions about wind turbines and solar PV panels. This paper assumes that all installed wind and solar PV infrastructure remains perfectly operational at all times and generates power purely as determined by the prevailing weather conditions. We do not attempt to account for infrastructure outages or performance degradation such as solar PV panel soiling, solar PV cell degradation, wind turbine equipment maintenance, wind turbine icing curtailment, electric grid connectivity interruptions, and so on. Additionally, all new wind and solar PV infrastructure placements are assumed to be accomplished with existing, commonly available turbines and PV panels.

Wind turbine modeling

All wind turbines (existing and new) are assumed to have hub heights of 80m, matching the elevation of wind speed data provided by the James et al. (2017) data set. Hourly wind power capacity factors are calculated as a fraction of nameplate capacity using the following generic wind turbine power curve equation:

$$CF_{wind} = 0.52 * \tanh[(0.34 * W_{80m}) - 2.6] + 0.48 \tag{2.1}$$

for all wind speeds between 3 m/s and 15 m/s, where W_{80m} is the 80m wind speed from the James et al. (2017) data set (see figure 2.1). Wind speeds between 15 m/s and 25 m/s result in $CF_{wind} = 1$; wind speeds lower than 3 m/s or higher than 25 m/s result in $CF_{wind} = 0$. This wind turbine power curve approximates the wind turbine power curve presented in Wan et al. (2010).

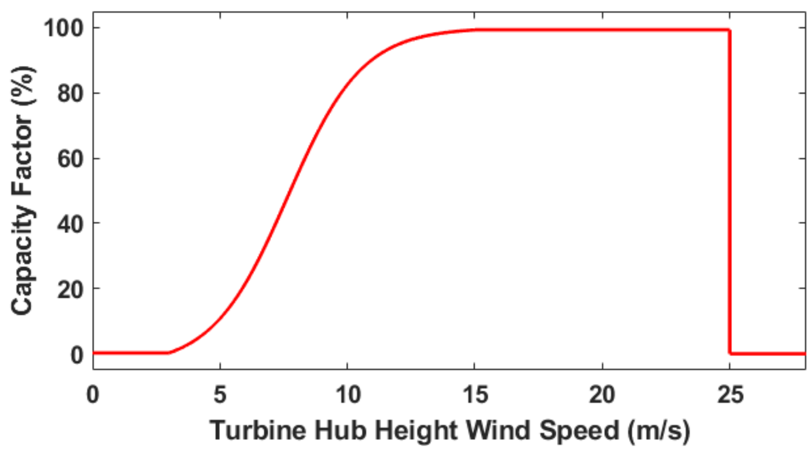

Figure 2.1: Wind turbine power generation curve

Solar PV panel modeling

Hourly solar PV panel capacity factors are calculated as a fraction of nameplate capacity using information about the solar PV panel mounting type, mounting location, and orientation relative to the Sun. All solar PV infrastructure is assumed to be either fixed-angle solar PV (FAPV) panels or two-axis tracking solar PV (TPV) panels. The orientation of a solar PV panel along with its latitude, longitude, and local time zone (i.e. hours offset from Greenwich Mean Time) are used to calculate θ, the angle between the Sun's rays and the solar PV panel's normal vector at a given hour. All TPV panels are assumed to track the Sun perfectly and therefore have $\theta = 0°$ at all times. θ values for FAPV panels are calculated using Twidell and Weir's (2006) method as follows:

$$\theta = \arccos\left\{(A - B)\sin\delta + [C\sin\delta + (D + E)\cos\omega]\right\} \tag{2.2}$$

where:

$$A = \sin\phi\cos\beta \tag{2.3}$$

$$B = \cos\phi\sin\beta\cos\gamma \tag{2.4}$$

$$C = \sin\beta\sin\gamma \tag{2.5}$$

$$D = \cos\phi\cos\beta \tag{2.6}$$

$$E = \sin\phi\sin\beta\cos\gamma \tag{2.7}$$

and:

$$\beta = \text{PV panel tilt angle} \tag{2.8}$$

$$\gamma = \text{PV panel rotation angle} \tag{2.9}$$

$$\delta = 23.45 * \sin\left[\frac{360 * (284 + JD)}{365}\right] \tag{2.10}$$

$$\phi = \text{latitude} \tag{2.11}$$

$$\psi = \text{longitude} \tag{2.12}$$

$$\omega = 15(TZ - 12) + [(15 * LT) - (15 * TZ)] + [(15 * TZ) - \psi] \tag{2.13}$$

$$JD = \text{Julian day} \tag{2.14}$$

$$LT = \text{Local Time (hours)} \tag{2.15}$$

$$TZ = \text{Time Zone (hours offset from Greenwich Mean Time)} \tag{2.16}$$

Sunlight data from the James et al. (2017) data set are provided as sunlight fluxes normal to Earth's surface. Deriving the capacity factor of an inclined solar PV panel of either type therefore requires the calculation of R_b, the ratio of sunlight exposure on an inclined surface to the sunlight exposure on a horizontal surface. Using Duffie and Beckman's (2013) method, R_b is calculated as follows:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{2.17}$$

where:

$$\cos\theta_z = \cos\phi\sin\delta + \cos\phi\cos\omega\cos\delta \tag{2.18}$$

For overnight hours, R_b is set to zero. R_b is capped at 4 to limit artificial overproduction of solar power in hours very near sunrise and sunset. R_b is then used to calculate solar panel capacity factors, CF_{PV}, as follows:

$$CF_{PV} = \begin{cases} S_{JDS} * R_b & S_{JDS} \leq S_{CS} \\ S_{CS} * R_b & S_{JDS} > S_{CS} \end{cases} \tag{2.19}$$

where S_{JDS} is the solar irradiance at the surface in W/m^2 from the James et al. (2017) data set and S_{CS} is the estimated horizontal clear sky solar irradiance at the surface using Haurwitz's (1945) method:

$$S_{CS} = 1098 * \cos\theta_z * \exp\left\{\frac{-0.057}{\cos\theta_z}\right\} \tag{2.20}$$

Conversion of capacity factors to power generation

Wind and solar PV power generation per hour per James et al. (2017) data set grid box is calculated by multiplying the nameplate capacities of each type of generator with their respective capacity factor data. Wind turbines are assumed to generate alternating current (AC) power matching their nameplate capacities. Solar PV panels are assumed to produce direct current (DC) power at their nameplate capacities; AC power generation is determined by factoring in user-defined inverter losses.

CF_{wind} and CF_{PV} are linearly interpolated on a minutely basis to reduce power generation errors. If CF_{wind} and CF_{PV} were used to calculate hourly generation directly, only the weather conditions at the start of the hour would determine generation for the entire hour. For example, if a given location experiences calm winds at the start of an hour and strong winds at the start of the next hour, the entire intervening hour would have no wind power generation. Similarly, hours in which the Sun rises would erroneously have no solar PV power generation for the entire hour and hours in which the Sun sets would erroneously generate solar PV power after sunset. By interpolating generation between hours on a minutely basis, the general trends of the wind and sun resources intra-hour are captured, though some variability is undoubtedly missing as compared to the real-world meteorological conditions. Capturing this variability would require higher time resolution data which is not yet available.

2.3.3 Wind and solar PV land area needs

The REGS model aggregates wind and solar PV infrastructure land use to 3km by 3km grid boxes matching those of the James et al. (2017) data set. Existing wind and solar PV infrastructure, if provided, is first aggregated to the nearest grid box and then parameterized at a fixed rate of nameplate capacity per m^2. All subsequent wind and solar PV infrastructure is added in 60m by 60m (3600 m^2) increments.

All FAPV infrastructure is assumed to occupy land at a rate of 186 kW_{DC} per 60m by 60m plot (51.67 W_{DC} per m^2) and all TPV infrastructure is assumed to occupy land at a rate of 96 kW_{DC} per 60m by 60m plot (26.67 W_{DC} per m^2). FAPV land area intensity is drawn directly from Ong et al. (2013), while TPV use land intensity is slightly lower than the value reported in Ong et al. (2013) based on estimates of existing TPV facilities in the state of Vermont. Rooftop FAPV installations are treated as if they are ground-mounted and therefore occupy land.

All wind turbines are assumed to occupy land at a rate of 3,000 kW_{AC} per 60m by 60m plot (83.33 W_{AC} per m^2). All new and existing wind turbines, regardless of nameplate capacity, are assumed to have an 80m hub height to simplify capacity factor calculations. To prevent wind turbine overcrowding[2], total wind turbine capacity is

[2]Wind turbines cannot be placed directly next to one another as solar PV panels can due to the

capped at 27 MW_{AC} per grid box, equivalent to nine, 3MW_{AC} wind turbines per grid box or 3MW_{AC} per km^2. Additional direct land area impacts of wind turbines such as service roads, easements, electricity transformation and transmission infrastructure, service buildings, meteorological observation equipment, etc. are not included in this model. While these attendant secondary land area impacts are typically much larger than the footprint of a wind turbine itself, it is difficult to accurately and fairly parameterize these land area impacts given the variability in wind farm configurations (Denholm et al., 2009).

2.3.4 Modeling methods

The REGS model constructs new wind and solar PV infrastructure configurations by using weighted random number selection to determine the infrastructure type, infrastructure siting method, and finally the location of the new wind turbine or solar PV panel array within the desired domain. The model is initialized with parameters indicating which grid boxes within CONUS are included in the test domain, how much land within each test domain grid box is restricted for development, where existing wind and solar PV infrastructure exists in the test domain, the desired ratio of new FAPV nameplate capacity to new TPV nameplate capacity to new wind turbine nameplate capacity, the desired infrastructure siting methodologies and their relative frequency, and the desired modeling goal (e.g. a specific amount of total wind and solar PV nameplate capacity, land occupation, or TWh of annual electricity generation). Parameters that weight infrastructure type and infrastructure siting method to the user's specifications are also included.

inherent spacing required between wind turbines to maintain operational safety and downwind wake effects on neighboring wind turbines. This spacing is referred to in this work as *indirect land use*. The modeling restriction of 9 wind turbines per 9km^2 imposed here thus means that indirect land use is incurred at a rate of 1/3 km^2 per MW_{AC} of wind turbine capacity.

New wind and solar PV infrastructure placements are performed individually in an iterative process. Figure 2.2 provides a visual flowchart summary of the REGS model infrastructure siting process. First, infrastructure type is selected randomly based on the user-defined ratio of desired new infrastructure types. As the model runs, infrastructure types that are over-represented as a percentage of newly installed capacity in the model are excluded from selection. As subsequent infrastructure selections are made, the relative proportion of a particular infrastructure type recedes towards the desired ratio until ultimately it is under-represented and is made eligible for selection. This "rubber-banding" effect prevents the final infrastructure ratio from diverging substantially from the user's desired infrastructure ratio. In cases where the model is tasked to maximize electricity generation over other factors, this model behavior also gives each infrastructure type a proportionally fair chance to occupy the highest average electricity generation locations, particularly when grid boxes have both a high quality wind and sunlight resource. Once the infrastructure type is selected, one of three infrastructure siting methods is chosen. New infrastructure can be placed to maximize electricity generation, to occupy grid boxes where other infrastructure of its own type is already located (hereafter referred to as *clustering*), and randomly. Finally, the model randomly selects the grid box which will receive the new infrastructure placement, subject to existing direct and indirect land area occupation, land area restrictions, and user-defined siting preferences. The probability of a given grid box receiving the new infrastructure placement depends on the siting criteria selected and how much bias is given towards high quality grid boxes versus low quality grid boxes. If a new wind turbine is being placed to maximize generation, for example, the model scales the estimated annual TWh generation of each grid box in the domain by a user-defined exponent. Next, the cumulative sum of these values is calculated and site selection probabilities for each grid box are assigned based on the grid box's share of the cumulative sum. Finally, a random number draw determines which eligible grid box receives the new wind turbine or solar PV panel array. The additional land use incurred and electricity generated by the new infrastructure is added to the existing wind and solar PV infrastructure, thus completing the cycle. If the most recent infrastructure placement does not break the target modeling threshold, the model begins the infrastructure placement process anew. Otherwise, the model reports out the locations and amounts of new wind and solar PV infrastructure deployed by the model.

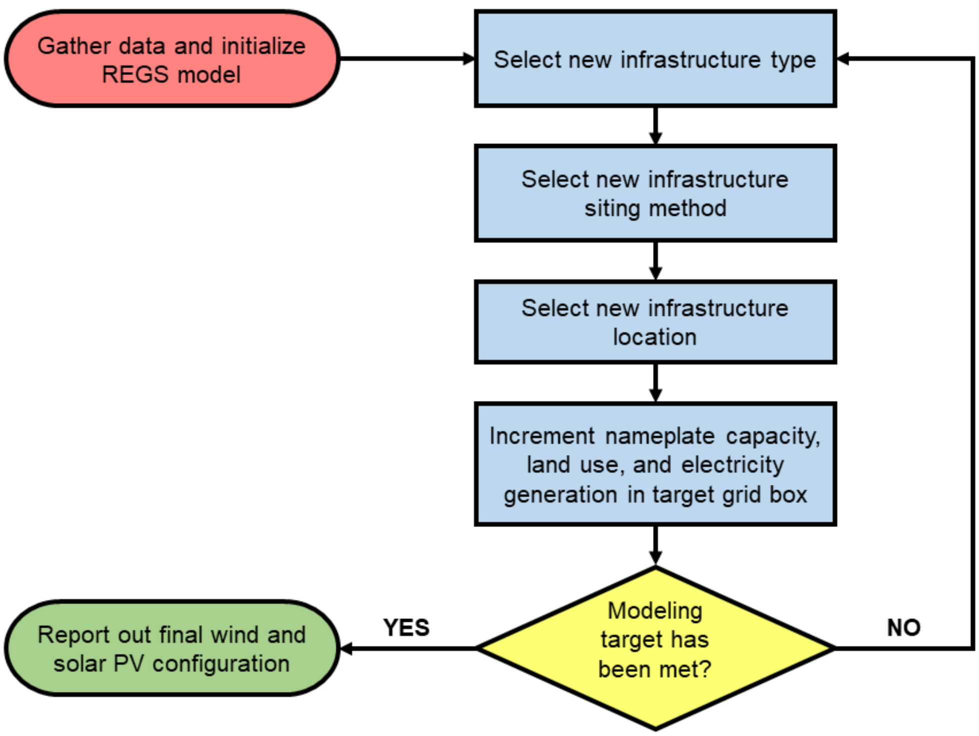

Figure 2.2: REGS model flowchart
[REGS model flowchart (Chapter 2)]

2.4 Vermont Case Study

The remainder of this paper uses the REGS model to perform a case study of the state of Vermont and its SEGs. This case study aims to illustrate how different wind and solar PV infrastructure choices can be used to meet SEGs, how different wind and solar PV siting strategies can influence electricity generation returns, and the land use consequences of these choices.

2.4.1 Current statutory energy goals

Vermont has established several SEGs that govern electricity, heating/cooling, transportation, and other energy uses. These SEGs are catalogued in the state's 2016 Comprehensive Energy Plan (CEP) (Vermont Department of Public Service, 2016). The 2016 CEP establishes goals of meeting 90% of Vermont's total energy needs with renewable energy sources by 2050, with intermediate goals of 40% by 2035 and 25% by 2025. Additional sector-specific goals relevant to the present study include meeting 67% of electricity demand by 2025 and 75% of electricity demand by 2032 with renewable energy sources, meeting 25% of total energy demand with in-state renewable energy resources by 2025, and meeting 10% of electricity demand from distributed generation resources (e.g. rooftop solar PV, small-scale wind turbines, waste-to-energy systems, etc.) by 2032. Though this case study focuses on SEGs related to the electricity sector, it is likely that some fraction of presently non-electric energy consumption in Vermont and elsewhere will be electrified even under business-as-usual conditions. This study will therefore consider, in general terms, the potential increase in electricity demand in Vermont from increased electrification of non-electric energy demands. More generally, the 2016 CEP reiterates the state's long-term goal of limiting Vermont's overall greenhouse gas emissions in 2050 to 25% of the state's 1990 greenhouse gas emissions. Meeting this goal will likely require significant electrification of presently non-electric energy demands and, consequently, significant growth in the generation of low-carbon or carbonless electricity to meet these new energy demands.

2.4.2 Wind and sunlight resources

The state of Vermont is relatively small compared to other American states in terms of land area, population, and total energy consumption (US Energy Information Agency, 2018b). Significant portions of Vermont are covered by lakes, wetlands, and a variety of protected lands managed by local, state, and federal agencies. The majority of Vermont's protected lands lie along the Green Mountains and adjacent foothills which run north-south through the center of Vermont (see figures 2.3A and 2.3B). The Green Mountains also significantly influence Vermont's wind and sunlight resource quality. The western slopes and peaks of the Green Mountains are home to Vermont's highest mean wind speeds as indicated by the dark green stripe in eastern Chittenden, Addison, Rutland, and Bennington counties (see figure 2.3C). The lowest mean wind speeds in Vermont are found in the valleys immediately east (climatologically downwind) of the Green Mountains in Lamoille, Washington, and western Orange Counties as well as the broader Connecticut River valley along the eastern edge of Vermont. In figure 2.3D, the impact of the climatological rain shadow induced by the Green Mountains can be clearly seen. Areas east of the Green Mountains, particularly Windsor and Windham counties, are 10 to 30% sunnier than western Vermont. Mean solar irradiance is much less variable than mean wind speeds across the Vermont, however, with the windiest locations in Vermont having almost triple the mean wind speed of the calmest locations. Wind turbine electricity generation potential is therefore much more sensitive to siting than solar

PV generation in Vermont.

2.4.3 Existing wind and solar PV infrastructure

At the beginning of 2018, Vermont had approximately 149 MW_{AC} of wind turbines, 168 MW_{DC} of FAPV, and 19 MW_{DC} of TPV (Energy Action Network, 2019; see figure 2.4). The ratio of FAPV to TPV to wind turbine nameplate capacity in Vermont is thus 444 kW_{AC} to 56 kW_{DC} to 500 kW_{DC} per MW of total nameplate capacity. Rooftop FAPV capacity represents 58 MW_{DC} (34.4%) of the total FAPV capacity. Vermont's five active wind farms are located on or near mountain peaks, far from large populations centers.

Vermont covers a total of 25,146 km^2, of which 18,305 km^2 [72.8%] is not covered by surface water, wetlands, conservation and wildlife protections, or is otherwise restricted from development. Existing wind and solar PV infrastructure covers approximately 4.14 km^2 [0.017%] of Vermont[3]. Much of Vermont's solar PV capacity is located in and around the state's largest towns and cities, such as Burlington (Chittenden County), Middlebury (Addison County), Montpelier (Washington County), and Brattleboro (Windham County). Table 2.1 summarizes the distribution of solar PV generation capacity across Vermont's 14 counties and the size of each county. All Vermont counties have at least some installed solar PV capacity. Chittenden and Addison counties alone provide over a third of Vermont's solar PV capacity despite having only 15% of Vermont's land area.

[3] 4.14 km^2 of land area assumes rooftop solar PV panels are instead ground-mounted as laid out in section 2.3.3. This and other land area estimates made in this paper therefore represent a likely 'worst-case scenario' upper bound or overestimate of actual solar PV land use.

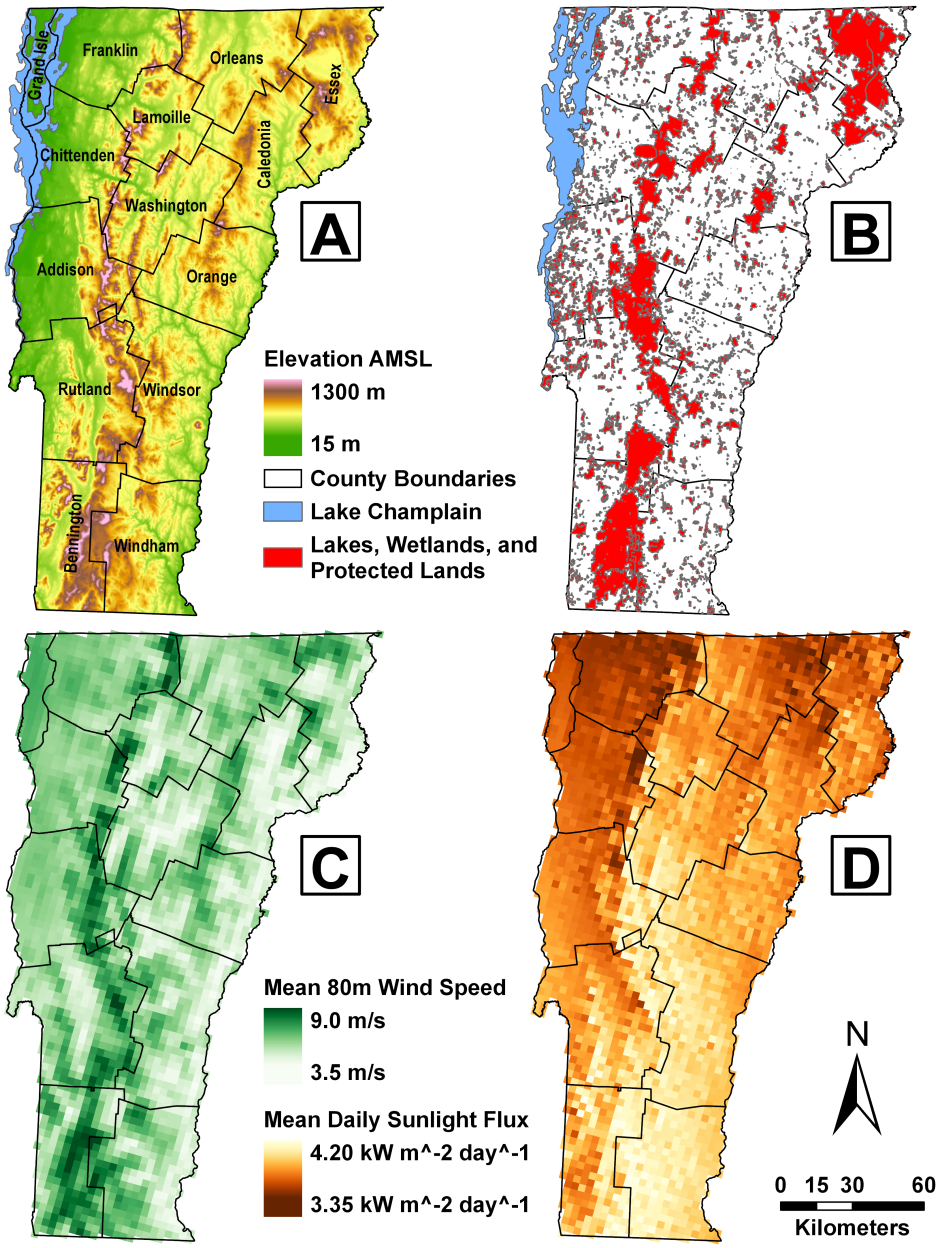

Figure 2.3: (A) Elevation above mean sea level, county names, and county boundaries (B) Lakes, wetlands, and protected lands (United States Geological Survey, 2014) (Vermont Center for Geographic Information, 2016)
(C) Mean wind speed at wind turbine hub height (James et al., 2017)
(D) Mean daily solar irradiance at Earth's surface (James et al., 2017).

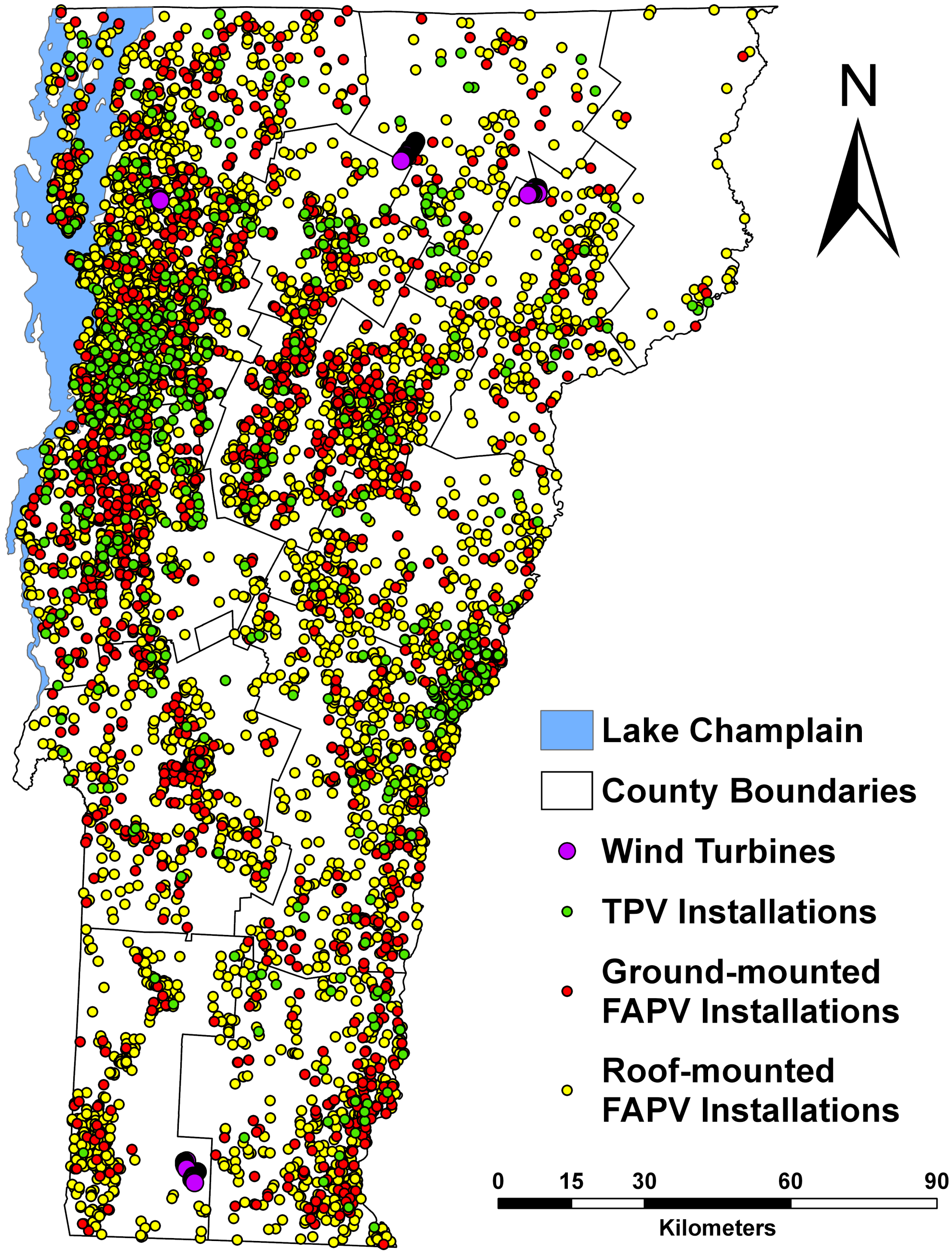

Figure 2.4: Estimated installed wind turbines and solar PV panels in Vermont as of January 2018. Wind turbines are marked individually; solar PV panels are grouped by installation and then marked. For the sake of map readability, dot size does not reflect installed generation capacity.

	Total Area (sq. km)	Total Area (% of VT)	Available Area (sq. km)	Available Area (% of VT)	Solar PV Capacity (MW_{DC})	Solar PV Capacity (% of VT)
Addison	2,114	8.41	1,276	6.97	31.055	16.55
Bennington	1,766	7.02	971	5.30	8.011	4.27
Caledonia	1,722	6.85	1,462	7.99	5.552	2.96
Chittenden	1,623	6.45	1,121	6.13	40.378	21.53
Essex	1,766	7.02	857	4.68	1.193	0.64
Franklin	1,817	7.22	1,374	7.51	14.056	7.50
Grand Isle	510	2.03	177	0.97	2.680	1.43
Lamoille	1,214	4.83	902	4.93	6.152	3.28
Orange	1,809	7.19	1,653	9.03	12.712	6.78
Orleans	1,889	7.51	1,547	8.45	7.075	3.77
Rutland	2,466	9.81	1,759	9.61	19.922	10.62
Washington	1,821	7.24	1,451	7.92	13.241	7.06
Windham	2,080	8.27	1,669	9.12	9.395	5.01
Windsor	2,548	10.13	2,086	11.39	16.102	8.59
TOTAL	25,146		18,305		187.504	

Table 2.1: Vermont land area and January 2018 solar PV infrastructure

2.4.4 Annual electricity imports, in-state generation, and consumption

Vermont relies on a range of in-state and out-of-state electricity generation capacity to meet its electricity needs. Of the 5.522 TWh of electricity sales made in Vermont in 2018, 1.392 TWh (25.2%) were met by in-state hydroelectric generation, 0.421 TWh (7.6%) were met by in-state biomass generation, 0.393 TWh (7.1%) were met by in-state wind generation, and 0.273 TWh (4.9%) were met by in-state solar PV generation, resulting in a total of 2.479 TWh (44.9%) of electricity demand being met by renewable electricity generation sources[4] (US Energy Information Agency, 2019). A further approximately 1.300 TWh (23.5%) of hydroelectric power is supplied to Vermont by Québec per year (Vermont Department of Public Service, 2016). The remaining 1.743 TWh (31.6%) of electricity demand per year is met by a range

[4]The REGS model estimates that Vermont's January 2018 wind and solar PV infrastructure would have generated an average of 0.366 TWh of wind power per year and 0.275 TWh of solar PV power per year when parameterized as discussed in sections 2.3.2, 2.3.2, and 2.4.5.

of conventional generation sources (primarily coal, natural gas, hydroelectric, and nuclear) located across New England. Total energy consumption in Vermont in 2016 was 128.7 trillion British Thermal Units (BTU), equivalent to 37.718 TWh of electrical energy (US Energy Information Agency, 2018a). Assuming a similar amount of total energy was consumed in 2018, electricity therefore represented just 14.64% of Vermont's total energy demand in 2018 (not including losses and inefficiencies in electricity generation, transmission, and distribution), resulting in wind and solar PV generation resources within Vermont meeting only 1.76% of Vermont's total energy demand in 2018.

Total annual electricity demand is only one measure of electricity system performance, however; the hour-by-hour fluctuations in electricity demand determine which generators (and therefore which fuels) are used by grid operators to meet electricity demand. Figure 2.5 shows mean hourly Vermont electricity demand (hereafter referred to as *load*) for the years 2013-2017, corresponding to each hour of weather data from the James et al. (2017) data set (ISO New England, 2018). Vermont load exhibits diurnal and seasonal patterns in-line with other developed societies in temperate climates. Load at any given time is influenced by the prevailing weather conditions in a given region (particularly temperature), time of day, day of the week, holidays, and normal electricity consumer behaviors. Grid operators obey a "supply follows demand" paradigm which means they must ramp generators up and down as load increases and decreases. The sharp load increase between 4AM and 7AM and corresponding load decrease between 6PM and 10PM are particularly challenging for grid operators to manage. As controllable generation sources are replaced by intermittent generators like wind and solar PV, it will be increasingly difficult for grid operators to meet load reliably and safely. Measuring the effectiveness with which wind and solar PV meet load in the absence of large-scale energy storage device deployment or coordinated wind and solar PV generation curtailment is therefore an important metric to consider when analyzing large-scale wind and solar PV infrastructure deployments.

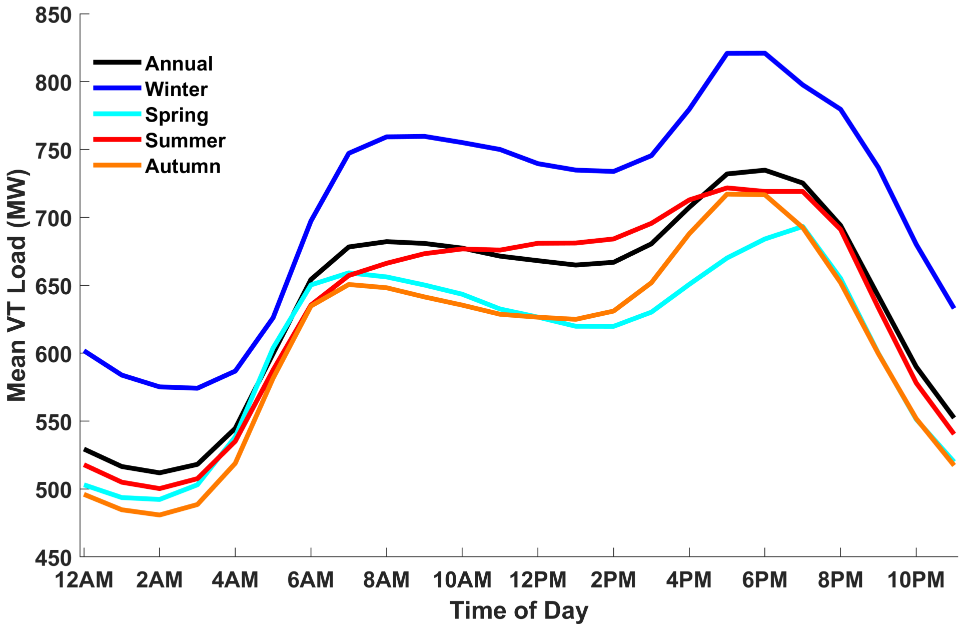

Figure 2.5: Average daily Vermont electricity demand for 2013 through 2017 (ISO New England, 2018). Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

2.4.5 Modeling assumptions and parameters

This paper applies a number of modeling assumptions and parameterizations to the REGS in order to minimize the operational differences of real-world wind and solar PV infrastructure deployments to simulated configurations. The assumptions and parameters listed here are user-controllable options within the REGS model, rather than inherent modeling choices such as the assumption of an 80m turbine hub height for all existing and new wind turbines.

- Reduction of sunlight and wind biases (see section 2.3.1). The James et al.

(2017) data set carries biases in both wind and sunlight which must be counterbalanced in order to produce more realistic electricity generation data. For the below case study, wind speeds are unmodified while irradiance is reduced by 15%. While wind speeds in the James et al. (2017) data set were verified against a sample wind turbine in the state of Colorado, it is not clear if the same biases are present in New England generally or Vermont specifically. Regardless, the modeled average annual wind power generation for Vermont's 149 MW_{AC} of wind turbines only slightly underestimates the actual reported Vermont wind power generation from 2018 (0.366 TWh versus 0.393 TWh, respectively). We therefore elect to leave the James et al. (2017) data set' wind speed data unchanged. Irradiance data were reduced by 15% to offset the sunny bias present in the northeastern CONUS as depicted in figure 15 of James et al. (2017).

- FAPV panel orientation. Solar PV panels are mounted at a wide variety of angles relative to the Sun and for a wide variety of reasons. While Energy Action Network (2019) provides basic information about the PV panel mounting type and mobility, the exact orientation of FAPV panels is not provided. In this case study, all FAPV panels are assumed to remain in one position year-round. Furthermore, all FAPV panels are assumed to be oriented equatorward (i.e. due south for all locations in the CONUS) and inclined at an angle of one half of local latitude. This orientation represents a more optimal panel orientation for summer solar PV generation potential and a balanced solar PV generation potential with respect to time of day (Yadav & Chandel, 2013).

- Power conversion losses. Both wind turbines and solar PV panels produce power which cannot be transmitted directly to the grid. Wind turbines typically generate power in AC but at a grid-asynchronous frequency. Solar PV panels produce DC power which can be used directly for local consumption (e.g. charging a battery or an electric vehicle) but must be converted to AC for transmission to the grid. In both cases, the power losses from the necessary conversion processes are small; for simplicity, this case study assumes they are zero. Inverters are typically built into wind turbines themselves and are therefore sized to match their nameplate capacities. Again, this case study assumes this to be the case and leaves wind turbine power generation unchanged. Solar PV panel arrays typically share inverters across panels given the small individual nameplate capacity of individual panels. The economics of inverters means that higher capacity and higher efficiency inverters are more expensive than lower capacity and lower efficiency inverters. Since solar PV panel arrays will rarely achieve their full rated power generation capacity, it is generally uneconomical to pair solar PV panel arrays with inverters of matching capacities (Mondol et al., 2006). This case study therefore applies a 20% reduction in AC solar PV power generation relative to DC solar PV power generation to account for this inverter sizing discrepancy.

2.5 Results

To illustrate how different SEG-compatible wind and solar PV configurations compare on total infrastructure needs, land area, and load satisfaction, a range of potential wind and solar PV configurations for the state of Vermont are developed and examined. First, we examine how Vermont's existing wind and solar PV infrastructure performs as compared to hypothetical alternative arrangements of the same amounts of infrastructure. Second, we construct and analyze a range of expanded wind and solar PV infrastructure deployments that satisfy four Vermont SEGs using ratios of wind and solar PV infrastructure that match the initial infrastructure deployment. Third, we construct SEG-compliant infrastructure configurations that extend the initial wind and solar PV configuration solely using wind turbines or solely using solar PV panels. Fourth, each of the above wind and solar PV infrastructure configurations is tested against real-world Vermont load data to assess its ability to meet load. These results, in combination, provide insights on the amounts of wind and solar PV infrastructure needed to satisfy SEGs and the general strengths and weaknesses of each as a potential pathway for renewable, low-carbon electricity provision in Vermont.

A combination of four SEGs, as described in Vermont Department of Public Service (2016), form the basis for future wind and solar PV infrastructure deployment targets analyzed in this paper. The four SEGs chosen for testing are:

- Meet 100% of Vermont's electricity demand with renewable energy sources
- Meet 25% of Vermont's total energy demand with renewable energy sources
- Meet 25% of Vermont's total energy demand with in-state renewable energy sources

- Meet 40% of Vermont's total energy demand with renewable energy sources

These targets correspond to approximately 5.5 TWh, 9.4 TWh, 9.4 TWh, and 15.1 TWh of electricity per year, respectively (US Energy Information Agency, 2018a). In order to set appropriate target levels of total new wind and solar PV electricity generation needed, existing renewable electricity generation detailed above (not including existing wind and solar PV generation) must be deducted. All 1.8 TWh of annual Vermont renewable electricity generation not derived from wind or solar PV plus the 1.3 TWh of hydroelectricity imported annually from Québec can be deducted from the first, second, and fourth SEG targets. Only the approximately 1.8 TWh of in-state annual Vermont renewable electricity can be deducted from the third SEG target. The final annual wind and solar PV electricity generation targets to be examined are therefore 2.4 TWh, 6.3 TWh, 7.6 TWh, and 12.0 TWh. These scenarios represent approximate increases of wind and solar PV electricity generation in Vermont relative to January 2018 by a factor of 3.5, 9.5, 11.5, and 18, respectively. The nameplate capacity, land area, and electricity generation data reported in the proceeding tables and figures reflect the mean and standard deviation of 50 identically parameterized model runs. Differences between model runs arise from variations in random number selections that determine infrastructure type selection and site selection as discussed in section 2.3.4. Figures that depict wind and/or solar PV infrastructure deployments show only one representative result of the 50 total iterations.

2.5.1 Evaluating Vermont's current wind and solar PV infrastructure

As a first step towards building SEG-compatible wind and solar PV infrastructure configurations, we examine the electricity generation performance of Vermont's existing wind and solar PV infrastructure relative to two hypothetical infrastructure redeployments. The first alternative siting method strongly biases infrastructure placements of both types towards high annual electricity generation locations within the domain. This siting strategy, referred to hereafter as 'maximum generation', does not involve any optimization methodologies. The second alternative siting method is a simple random placement scheme and is referred to as such hereafter. This siting scheme acts as a control scenario for comparison against other siting methods and to the existing Vermont wind and solar PV configuration.

Figure 2.6 depicts example deployments of wind and solar PV under each alternative siting scheme relative to the status quo deployment. As expected, wind turbines are located along the spine of the Green Mountains in central Vermont under the maximum generation scenario. Solar PV panels are predominantly located in southern and eastern Vermont, matching the state's strongest sunlight resource areas east of the Green Mountains. Both of the maximum generation scenario configurations differ sharply from the actual deployment of wind and solar PV infrastructure in Vermont. Most of Vermont's existing wind turbines, while sited on locally high terrain, do not capture the state's peak mean wind speeds. Likewise, much of Vermont's best solar resource is only partially utilized at best by the present solar PV panel deployment. As is discussed in later sections of this paper, maximizing generation output is but one of many criteria that prospective developers must consider when selecting a plot of land for wind and solar PV energy infrastructure installation. Random placement of both wind turbines and solar PV panels creates infrastructure deployments that resemble neither the actual deployment nor the maximum generation scenario.

Table 2.2 shows the corresponding mean annual electricity generation performance of the two alternative wind and solar PV infrastructure siting methods and of the initial Vermont wind and solar PV infrastructure configuration. As expected, the maximum generation siting methods produce infrastructure configurations that outperform Vermont's actual configuration. Mean annual solar power production is approximately 6% higher in the maximum generation scenario as compared to the initial Vermont configuration while wind power generation nearly doubles. The random placement scenario also yields slight improvements in both wind and solar PV mean annual generation as compared to the initial Vermont configuration, though the difference between the means (0.011) is smaller than the standard deviation of the random placement mean annual electricity generation (0.016).

	Max. generation	Random placement	Initial config.
Wind	0.727* $\pm$ 0.002	0.373* $\pm$ 0.016	0.366
FAPV	0.248 $\pm$ 0	0.238 $\pm$ 0	0.235
TPV	0.042 $\pm$ 0	0.040 $\pm$ 0	0.039
TOTAL	1.017 $\pm$ 0.002	0.651 $\pm$ 0.016	0.640

Table 2.2: Mean annual electricity generation (TWh) from hypothetical alternative Vermont wind and solar PV infrastructure arrangements. NOTE: For modeling simplicity, 150 MW_{AC} of wind turbine capacity (fifty 3 MW_{AC} wind turbines) were sited in the maximum generation and random placement scenarios. This puts the 'maximum generation' scenario and 'random placement' scenario at a 1 MW_{AC} advantage against Vermont's initial wind turbine nameplate capacity.

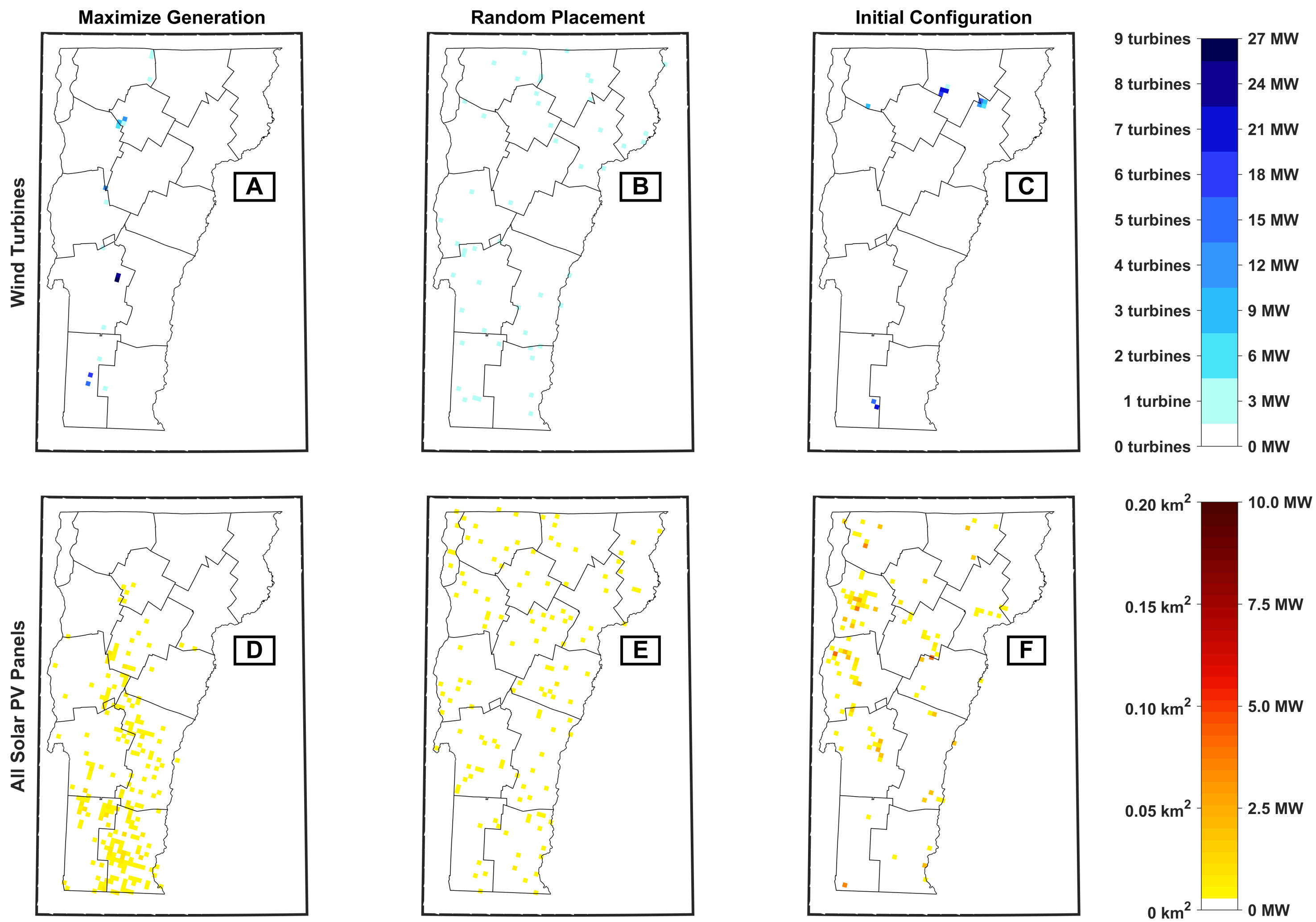

Figure 2.6: Actual and hypothetical alternative Vermont wind and solar PV infrastructure arrangements

2.5.2 Land area impacts of Vermont SEG-compatible deployments

The rest of section 2.5 presents modeled expansions of Vermont wind and solar PV infrastructure using three siting methods. The first two siting methods used are the maximum generation and random placement methods described above; the third siting method used is named 'clustering'. The clustering siting method weights each grid box according to how much land is already occupied by a given wind or solar PV infrastructure type both within the grid box and in neighboring grid boxes. Only infrastructure-type land area in adjacent, cardinal direction grid boxes is included in the weighting calculation and adjacent infrastructure-type land area is weighted at 50% as compared to the grid box's own infrastructure-type land area. The clustering siting method represents an approximate 'business as usual' wind and solar PV growth approach in which regions that currently host wind and/or solar PV infrastructure will receive more of it and areas that currently do not host wind and/or solar PV infrastructure will rarely, if ever, receive more. Siting of new wind and solar PV infrastructure under the clustering siting method, as with the other two siting methods, adheres to land use protections and competition for land availability among infrastructure types.

A total of twelve scenarios were generated using the REGS model, one for every combination of one of three siting methods and one of four Vermont SEGs as outlined at the start of section 2.5. Figures 2.7 and 2.8 show the deployment patterns of new wind and solar PV infrastructure for eight of the twelve scenarios. For brevity, the random placement scenarios are not depicted. Infrastructure siting patterns persist between the hypothetical maximum generation wind and solar PV configurations from the previous section and the expanded SEG-compatible deployments shown here. New wind turbines are located almost exclusively along the spine of the Green Mountains (figures 2.7A through D) to harness the Vermont's peak mean wind speeds and solar PV panels are predominantly located in Windsor and Windham counties (figures 2.8A through D) in line with Vermont's peak mean irradiance values. As annual electricity generation targets rise, wind turbines steadily saturate the best wind energy resource locations along the Green Mountains and begin to spread to Essex County in northeastern Vermont (figure 2.8D). Clustering-driven siting for wind (figures 2.7E through H) and solar PV (figures 2.8E through H) largely follow the spatial pattern set by Vermont's initial wind and solar PV infrastructure configuration. Wind turbine siting in these scenarios results in large, localized deployments surrounding the four existing clusters of wind turbines that grow steadily as electricity generation targets rise. New solar PV panel installations are much more diffuse throughout Vermont thanks to the state's initial solar PV panel distribution. A few individual grid boxes in Chittenden and Rutland counties exceed MW_{AC} of solar PV panel nameplate capacity and 0.5 km^2 of total solar PV land use (figure 2.8H).

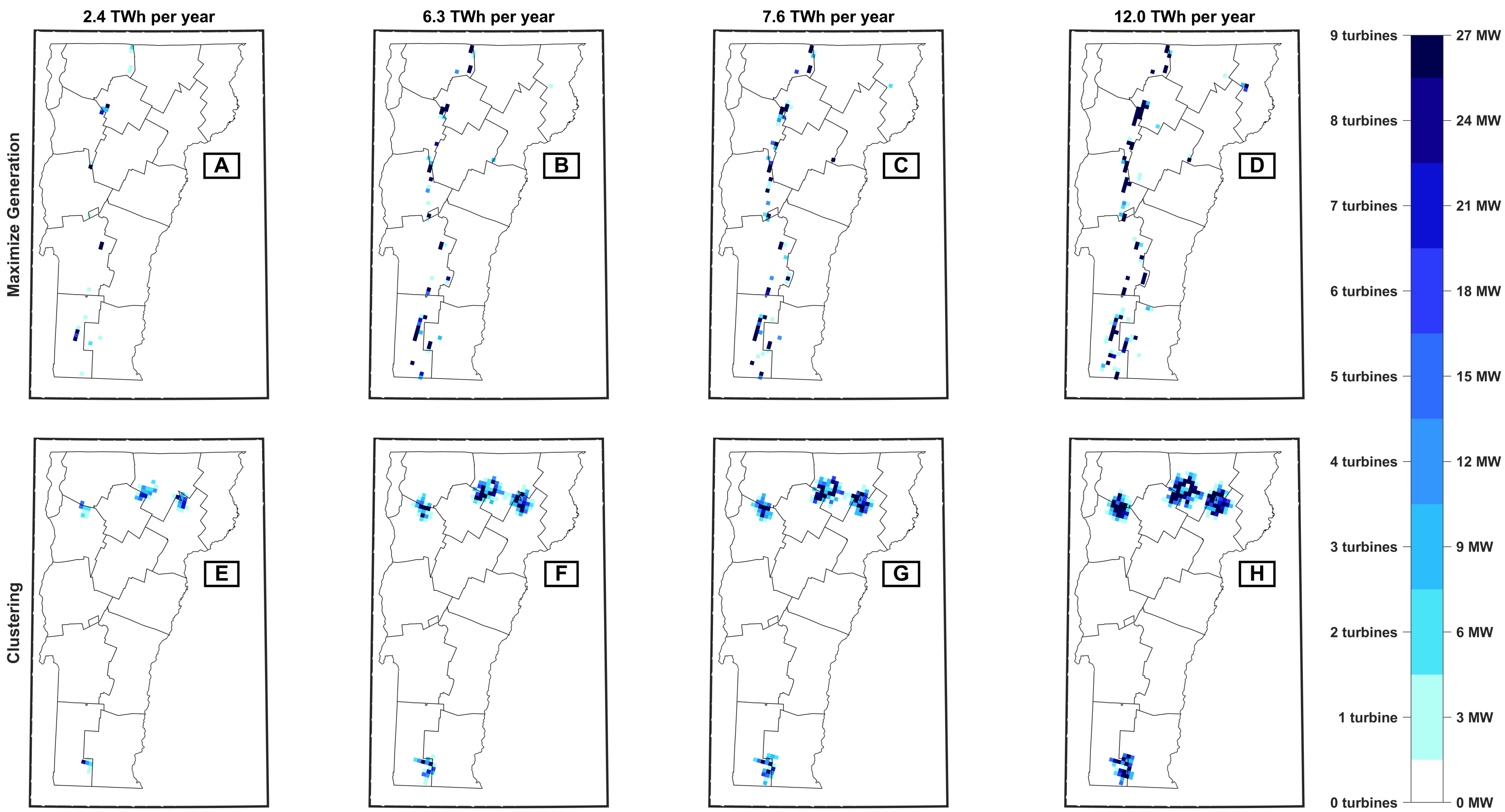

Figure 2.7: Total modeled Vermont wind turbine infrastructure growth under maximum generation and clustering siting methods

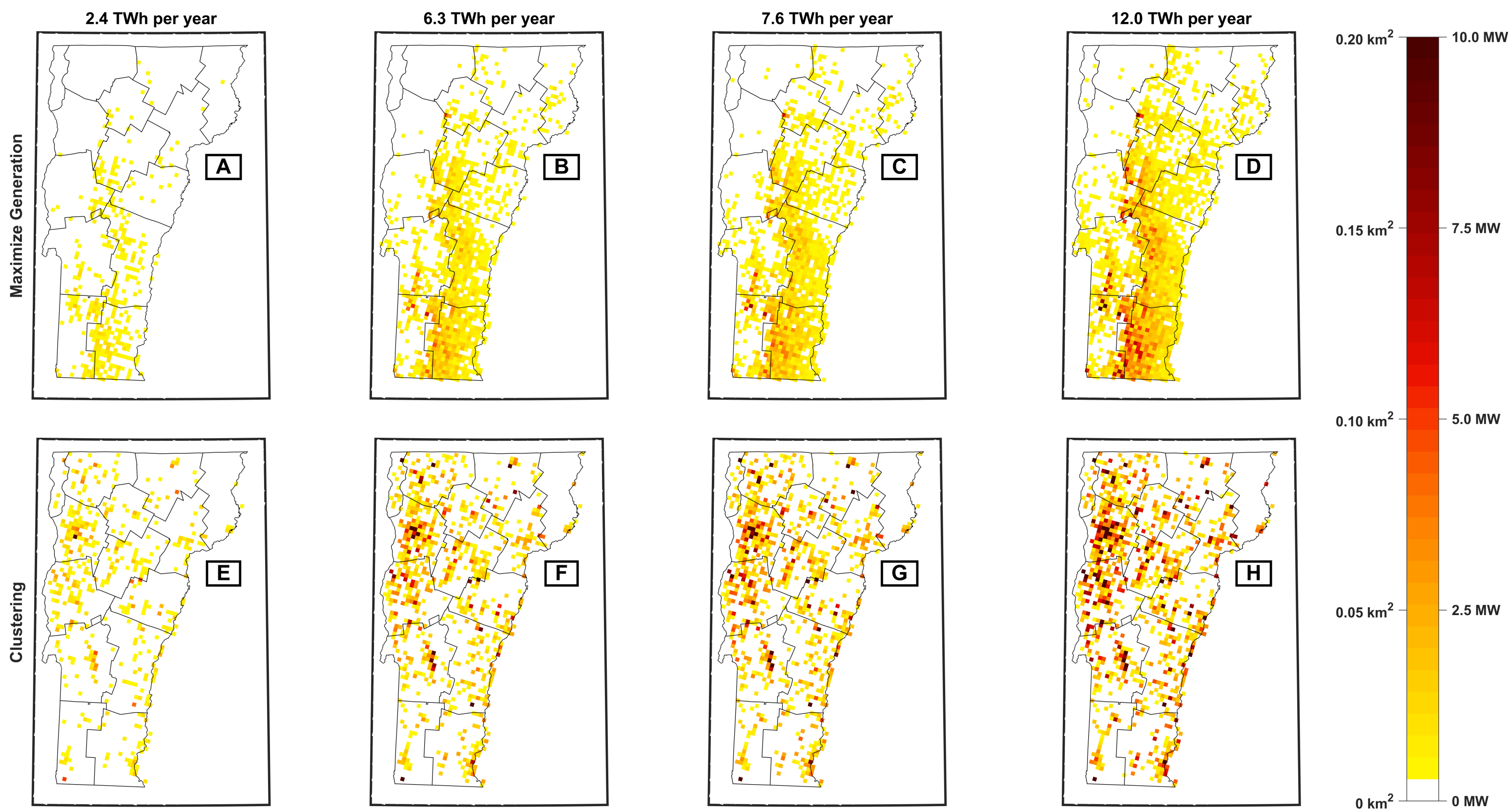

Figure 2.8: Total modeled Vermont solar PV panel infrastructure growth under maximum generation and clustering siting methods

Figures 2.9 reveals the mean wind and solar PV infrastructure requirements to meet each SEG. As expected, maximum generation siting achieved the SEG using the least amount of infrastructure across all four SEGs. As little as 0.92 GW_{AC} of wind and solar PV infrastructure, including the 0.34 GW_{AC} of infrastructure already installed, is sufficient to meet the first SEG of meeting 100% of Vermont's annual electricity needs through renewable energy resources. In contrast, both the random placement and clustering siting methods require over 1.2 GW_{AC} of total wind and solar PV infrastructure. This approximately 35% jump in total infrastructure requirements between the maximum generation and the random placement/clustering siting method grows to over 44% for the three higher SEG thresholds. The disparity is such that a nearly equivalent amount of wind and solar PV infrastructure (approximately 4.3 GW_{AC}, or more than ten-fold the amount of existing wind and solar PV infrastructure in Vermont presently) could either be used to generate 7.6 TWh of electricity per year under a random siting regime or nearly 12.0 TWh of electricity per year when sited to maximize generation. Clustering siting scenarios only marginally outperform random placement scenarios across the four SEG thresholds, largely due to the placement of existing wind turbines in sub-peak wind resource regions.

Figure 2.10 shows the corresponding mean land area needed to accommodate each SEG-compatible infrastructure deployment. Land area requirements scale linearly with nameplate capacity because of the fixed land area per unit nameplate capacity and fixed FAPV to TPV to wind turbine capacity parameterizations. As little as 11 km^2 of land is needed to accommodate a SEG-compatible 2.5 TWh/yr infrastructure configuration, which represents less than 0.1% of Vermont's total eligible land area. The most aggressive SEG target and largest land footprint infrastructure deployment combination, 12 TWh/yr achieved through random placement, requires only 77

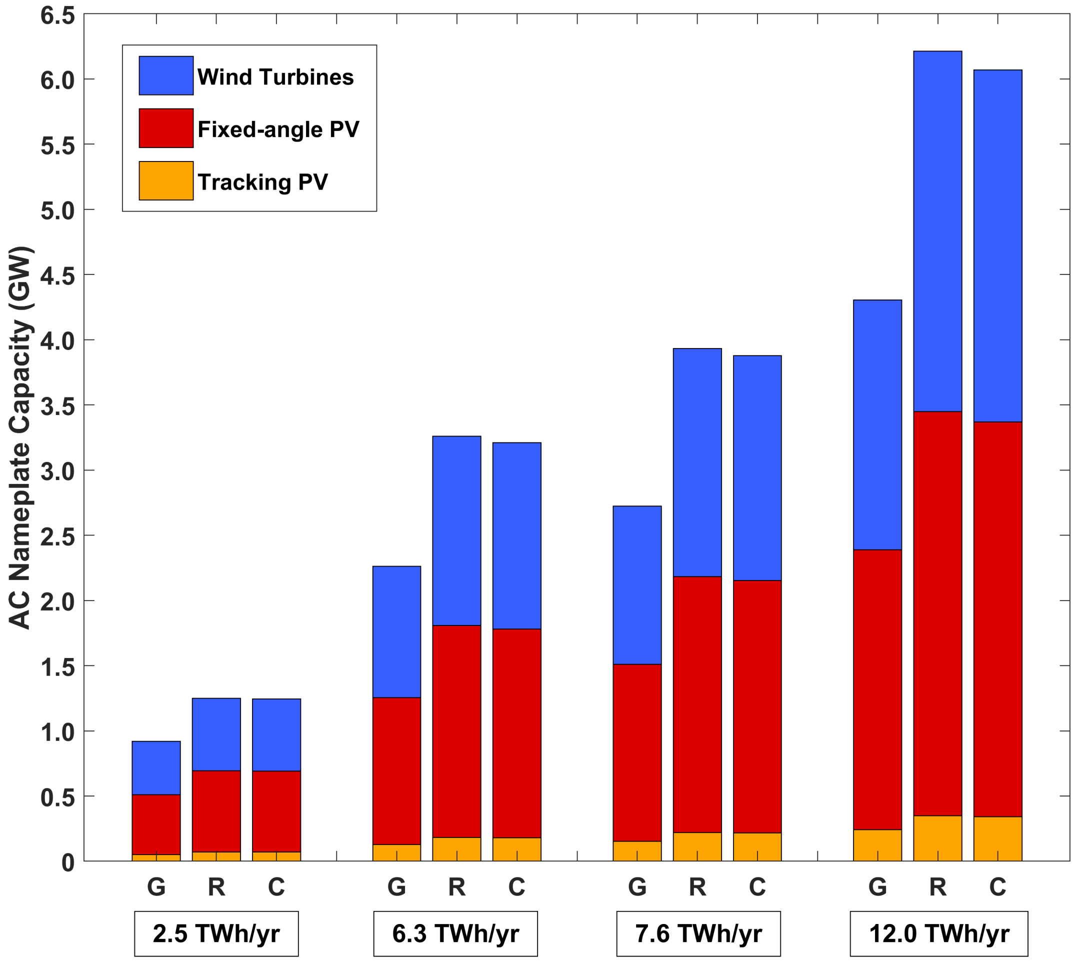

Figure 2.9: Nameplate capacities of SEG-compatible wind and solar PV infrastructure deployments. G: maximum generation siting; R: random placement; C: clustering.

km^2 [0.42%] of Vermont's eligible land. The equivalent maximum generation siting scenario only requires 53 km^2 [0.29%] of Vermont's eligible land.

Of the three infrastructure types modeled, wind turbines directly occupy far less land per unit of nameplate generation capacity as compared to FAPV and TPV panels. Across all twelve test scenarios, wind turbines represent 44.4% of the total nameplate generation capacity and at least 57% of the mean annual electricity generation but only 4.3% of the total infrastructure land area footprint. In Vermont's case, this makes wind turbines a superior choice relative to solar PV panels of either

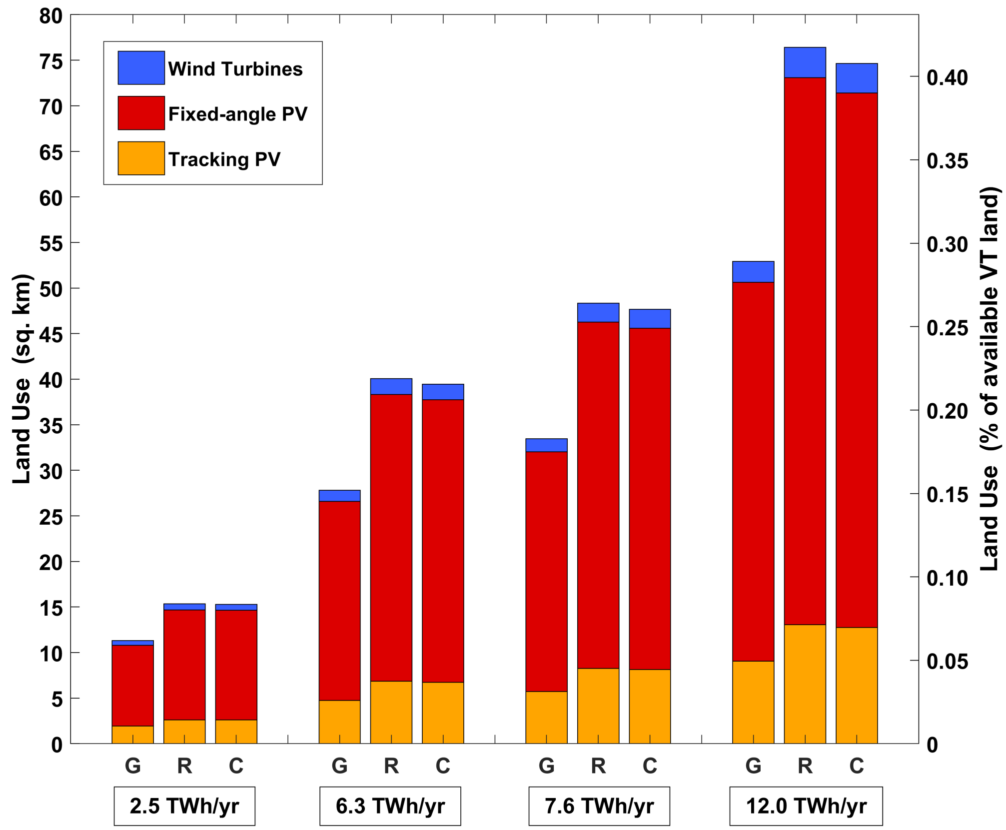

Figure 2.10: Land area requirements of SEG-compatible wind and solar PV infrastructure deployments. G: maximum generation siting; R: random placement; C: clustering.

type for maximizing annual electricity generation returns and minimizing land use. This does not mean, however, that wind energy is without its landscape impacts; this topic is revisited in depth in the proceeding discussion section. Furthermore, the relative strength of the wind and sunlight resources in a particular region will strongly influence the advantages of wind turbines to solar PV panels in electricity generation per unit land. Finally, the abundance or scarcity of a region's highest quality wind and sunlight resources will modulate how advantageous one infrastructure type is over another as total electricity generation targets increase. In the Vermont case, the state's highest quality wind and sunlight resources are not significantly exhausted in meeting the four SEGs tested due to the state's relatively low population density (reducing the amount of infrastructure and therefore land needed to meet SEGs) and the proportionally large areas of the state that have the highest mean wind speeds and sunlight exposure. Further comments on the specificity of this case study's findings to Vermont can be found in the proceeding discussion section.

2.5.3 100% wind and 100% solar PV deployments

We now examine two alternative infrastructure growth ratios under the same siting strategies to capture a more complete range of potential SEG-compatible wind and solar PV infrastructure deployment pathways. A wind-only or solar PV-only infrastructure deployment would be the only viable paths to achieving a SEG-compatible wind and solar PV-powered electricity system under a strict statewide constraint on development of one or the other infrastructure type. Examples of these constraints could include severe disruption of wind turbine or solar PV panel manufacturing, a legislative moratorium on further wind turbine or solar PV panel installation, and a grid operator-imposed moratorium on intermittent electricity generator interconnections.

Figure 2.11 shows how wind-only and solar PV-only infrastructure additions would satisfy Vermont's 12.0 TWh/year SEG under the maximum generation, random placement, and clustering siting methods. The spatial patterns of new infrastructure siting in these scenarios are consistent with those found previous scenarios. In figures 2.11B, 2.11D, and 2.11E, almost all of Vermont receives some new infrastructure except for grid boxes that fall entirely within protected parcels of land. Wind turbine clustering, as seen in figure 2.11C, shows that areas in Caledonia, Orleans, Windham, and Franklin counties that are as much as 24 kilometers away from existing wind turbine installations at present now have substantial wind turbine infrastructure installations. Though the total amount of land occupied by these high penetration scenarios on a statewide and gridbox by gridbox basis is relatively low, it is clear that large-scale wind turbine and solar PV panel deployments will impact Vermonters and Vermont landscapes in every county and almost every community in the state.

Total nameplate capacity requirements for meeting 12.0 TWh/year of electricity generation rise sharply when implementing an all solar PV panel deployment as compared to a mixed infrastructure scenario (see figure 2.12). Whereas just 4.3 GW_{AC} of wind and solar PV infrastructure is needed under the current ratio, maximum generation scenario, over 7.4 GW_{AC} of new solar PV panels are required under the solar PV-only, maximum generation scenario. In contrast, the wind-only, maximum generation scenario requires less than 3 GW_{AC} of new wind turbines to be constructed.

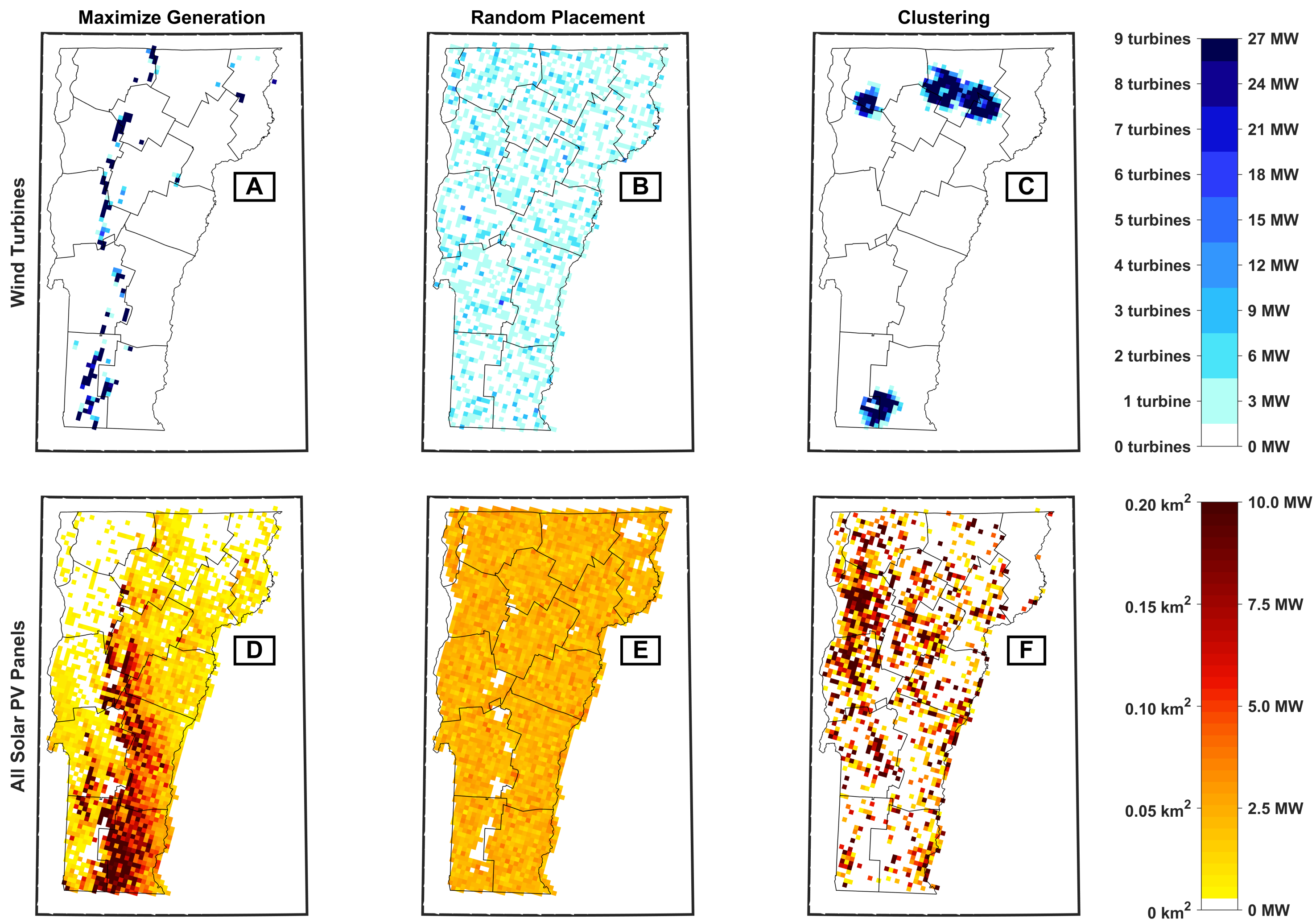

Figure 2.11: 100% wind turbine and 100% solar PV panel deployments to meet Vermont's 12.0 TWh/yr SEG

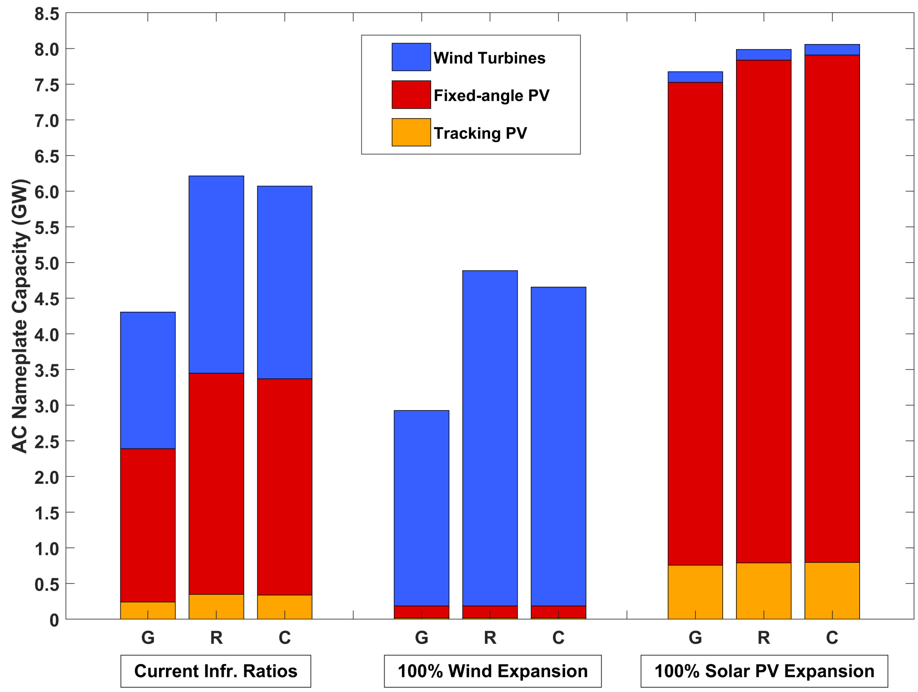

Figure 2.12: Nameplate capacities of 12.0 TWh/yr SEG deployments. G: maximum generation siting; R: random placement; C: clustering.

Land area requirements of the wind-only and solar PV-only infrastructure deployments are shown in figure 2.13. While many of the scenarios tested here produced infrastructure deployments that spread over most or all of Vermont, none of the test scenarios resulted in total wind and solar PV land area exceeding 1% (183 km^2) of Vermont's eligible land. Among scenarios that site at least some wind turbines, no scenario exceeded 0.5% of (92 km^2) Vermont's eligible land. Once again, wind turbines offer the highest nameplate capacity to direct land area efficiency in Vermont. For example, the wind-only, maximum generation scenario occupies just 7.3 km^2 of land, less than double the land occupied by all of Vermont's existing wind and solar PV infrastructure.

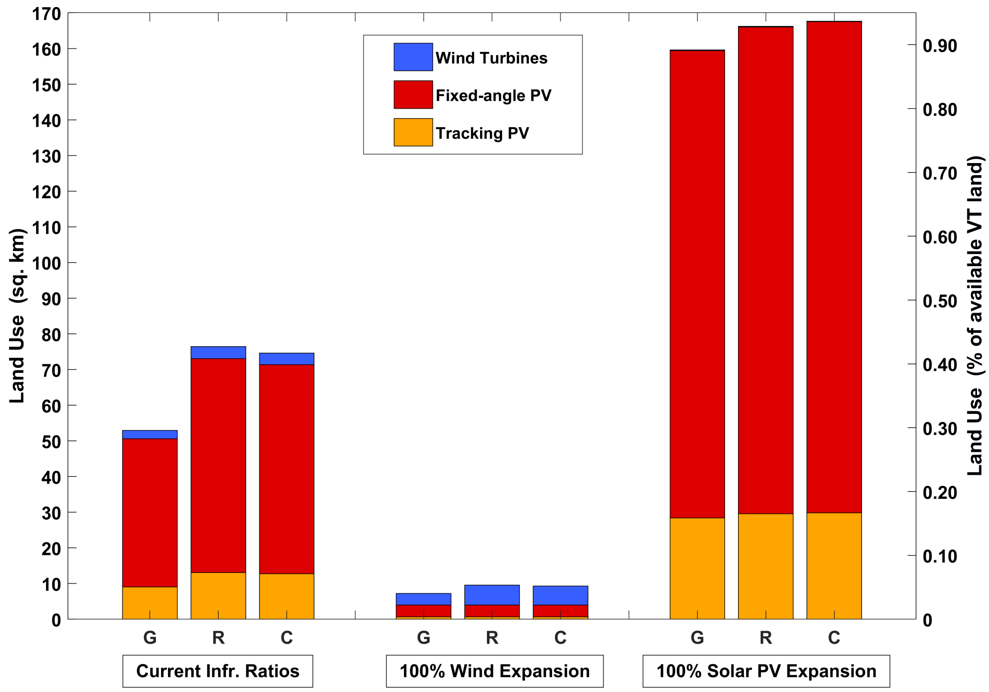

Figure 2.13: Land area requirements for 12.0 TWh/yr SEG deployments. G: maximum generation siting; R: random placement; C: clustering.

2.5.4 Assessing wind and solar PV deployments versus hourly load

Finally, we examine each wind and solar PV infrastructure deployment scenario for its performance relative to real hourly Vermont load data. Modeled hourly electricity generation data for the years 2013 to 2017 are compared to real Vermont statewide hourly load data for the same period to assess the effectiveness of all 21 test scenarios in satisfying hourly load in the absence of energy storage and other electricity generation resources. Figure 2.14 shows that across all test scenarios except for the 2.4 TWh/year and 100% solar PV deployments, maximum generation siting method deployments yield increased annual load satisfaction of between 5 and 8% relative to random siting and clustering siting method deployments. In the remaining two scenario groups, each siting method yields nearly identical load satisfaction performance (approximately 43% and 52% of total load met, respectively) but for different reasons. In the 2.4 TWh/year scenarios, there are very few hours in which load is completely met by wind and solar PV, meaning that almost all of the 2.4 TWh of electricity generated per year by each configuration is used to meet load. As figure 2.15 confirms, only a negligible amount (less than 0.005 TWh [0.9%]) of annual electricity generation is produced in excess of hourly load over the entire five year test period. Conversely, the 100% solar PV scenarios generate enormous amounts of surplus electricity generation (in excess of 9 TWh [75%]) per year. The over 7 GW_{AC} of solar PV panels placed across Vermont in these scenarios (see figure 2.12) easily meet and exceed Vermont's hourly load during most daylight hours but are incapable of generating electricity at night, thus leaving unavoidable deficits in load satisfaction. Also of note is the inferior performance of the wind-only and solar PV-only scenarios relative to the 12.0 TWh/year, current ratio scenarios. This result suggests that there are some advantages in leveraging a mix of wind and solar PV infrastructure for satisfying load as compared to wind-only and solar PV-only infrastructure deployments.

Figures 2.14 and 2.15 also reveal that as increasing amounts of wind and solar PV infrastructure are installed, regardless of siting strategy, the marginal increases in load met by wind and solar PV decrease sharply. The approximately 2 GW_{AC} of additional wind and solar PV nameplate capacity in the 6.3 TWh/year, maximum generation scenario relative to the initial wind and solar PV infrastructure configuration carries annual load met from 18.1% to 82.5%. The next 2 GW_{AC} of additional wind and solar PV nameplate capacity needed to achieve the 12.0 TWh/year threshold yields only a 9.3% increase in annual load met to 91.8%. The principle cause of this pattern is the frequency of low wind, low (or no) sunlight weather conditions. Given an infinite

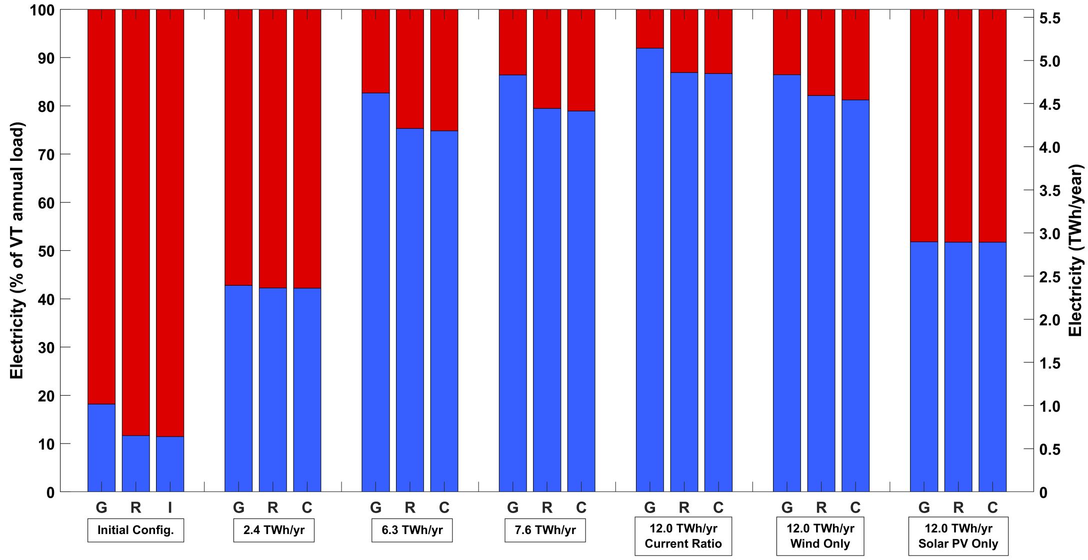

Figure 2.14: Mean annual Vermont load met by in-state wind and solar PV. G: maximum generation siting; R: random placement; I: Initial Configuration; C: clustering.

amount of wind and solar PV infrastructure, there are some hours in which winds are calm, the sun does not shine, and wind and solar PV generators cannot produce electricity. These events, though infrequent, are inescapable hindrances for even large-scale wind and solar PV infrastructure deployments, particularly in relatively small geographic domains (Østergaard, 2008).

Figure 2.16 shows how each test scenario performs on a per-unit nameplate capacity basis with respect to overall electricity generation and load met. While electricity generation figures remain steady as each SEG is satisfied, marginal load satisfaction per unit of wind and solar PV infrastructure decreases steadily. Load satisfaction efficiency drops from 1,900 kWh per kW_{AC} in the real-world initial configuration to just 1,200 kWh per kW_{AC} in the 12.0 TWh/year, maximum generation scenario. Even the 100% wind energy scenarios, where electricity generation per unit capacity is well over 4,000 kWh per kW_{AC}, suffer degraded per-unit load satisfaction efficiency relative to the initial configuration. This trend comports with the diminishing marginal returns on new wind and solar PV infrastructure

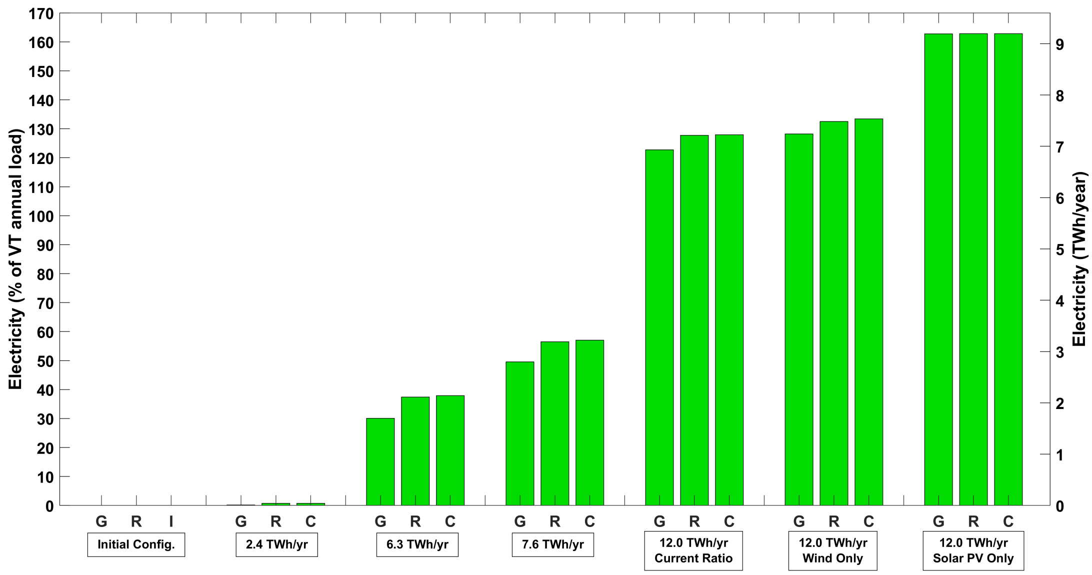

Figure 2.15: Mean annual surplus electricity generation for Vermont wind and solar PV versus hourly load. G: maximum generation siting; R: random placement; I: Initial Configuration; C: clustering.

discussed above.

2.6 Discussion

The foregoing case study demonstrates how more granular modeling of wind and solar PV infrastructure, the land area this infrastructure incurs, and the weather conditions this infrastructure relies upon for electricity generation can enable more realistic and tangible formulations of SEG-compatible electricity systems. The methods described here can be utilized anywhere in CONUS, provided that sufficient information about the location, size, and type of existing wind and solar PV infrastructure can be collected. Analyses of other states and regions in North America to compare and contrast with Vermont were hampered by the lack of datasets equivalent to Energy Action Network (2019). The diversity of potential pathways for meeting SEGs and broader goals like the "rapid and far-reaching transitions" called for by the IPCC

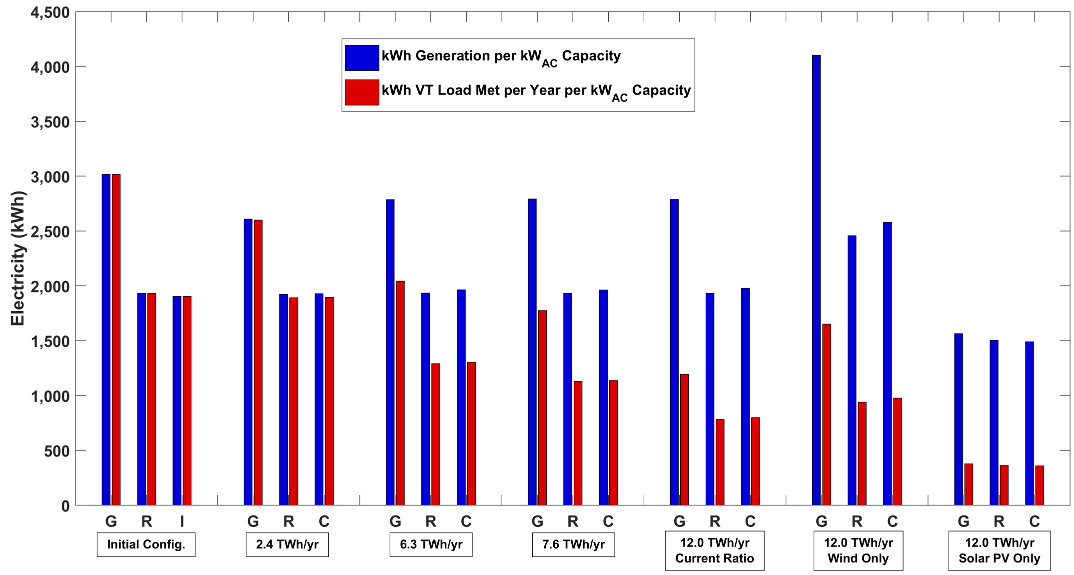

Figure 2.16: Vermont wind and solar PV electricity generation and load satisfied per kW_{AC} nameplate capacity.

means that this work only represents one part of the process for finding and delivering a consensus electricity system decarbonization solution (Intergovernmental Panel on Climate Change, 2018). Moreover, the solution that works for one region or community may not work for another. Based on the outcomes of this case study, wind turbines appear to be a superior choice for meeting Vermont's electricity needs in terms of operational efficiency (i.e. meeting electricity demand when it is demanded) and land area efficiency. This outcome should not be construed as a recommendation for Vermont to deploy wind turbines hastily or exclusively, nor is it a blueprint for the whole of North America to follow. Each region has different population levels, energy demand patterns, wind and sunlight resources, electric grid capacities, preferences, priorities, and so on; there is no one-size-fits-all solution. Instead, the Vermont case study demonstrates in general terms how the distance between energy policy goals and initial conditions can be bridged. The ultimate utility of this information is then unlocked when its findings are used to inform and initiate further analyses and stakeholder discussions. It is from these processes that the ultimate electricity system decarbonization pathways will be determined. To that end, we will now discuss a range of additional topics that interlock with and overlap the work undertaken here.

As noted, the Vermont case study shows that, among the three infrastructure types modeled, wind turbines provided both large, consistent electricity generation returns and minimal direct land area impacts. This will also be true of other regions of North America that have strong wind resources and particularly true of other locations with similar or lower quality sunlight resources. The full landscape impacts of wind energy are not fully captured in the above case study, however. As discussed briefly in section 2.3.3, wind turbine towers only directly occupy small parcels of land. Secondary land uses, both temporary and permanent, due to site preparation, service roads, and support infrastructure can significantly expand the true footprint of wind turbine installations. The visual impacts of wind turbine towers and rotating blades are also not captured in the model. These impacts represent a significant source of resistance to wind turbine siting among communities in Vermont and elsewhere. While the REGS model uses a rudimentary measure of wind turbine crowding to prevent oversaturation, it does not capture the potential visual impacts of wind turbines which undoubtedly influence the viability of some locations for receiving wind turbines (Pidala, 2017; Opalka, 2018). This is particularly true for many of the highest electricity generation locations in Vermont which are also typically the highest elevation locations in Vermont and therefore among the most visible locations in Vermont. Making like for like comparisons between wind turbines and solar PV panels in terms of land area is thus a somewhat flawed exercise. Better capturing the total landscape-level impacts of wind energy in future modeling iterations is a worthy area for future work.

Another key aspect of new energy infrastructure deployments to consider is the lifespan of the infrastructure. Like any other infrastructure type, wind turbines and solar PV panels have limited effective lifespans and must be replaced periodically. Wind turbines and solar PV panels typically have lifespans of between 20 and 30 years (Fthenakis & Kim, 2009). Once a wind turbine or solar PV panel array is due to be replaced, its electricity generation capacity is lost until new infrastructure is installed or a new installation is made elsewhere. This process is not captured in the REGS model since the model develops individual snapshots of infrastructure deployments rather than timeseries. While infrastructure replacement means that more efficient wind turbines or solar PV panels can be installed, it also allows for land leases to expire and generation capacity to be lost. Capturing these factors in future modeling activities could also enhance the utility of this work.

Rooftop solar PV panels are not distinguished from ground-mounted solar PV panels in this case study which means that rooftop solar PV panels incur land occupation. Quantifying rooftop solar PV panel siting suitability and electricity generation potential is an active area of research (Wiginton et al., 2010; Gagnon et al., 2018). More explicit modeling of rooftop PV panel siting could both improve the accuracy of the model and reduce the modeled land area footprint of solar PV panel infrastructure. This could enhance the relative strength of solar PV panels against wind turbines in land area efficiency evaluations and provide better estimates of a given region's potential rooftop solar PV capacity. Rooftop solar PV panels can also partially or completely meet local household electricity demand in some situations and, in aggregate, significantly influence the grid's net electricity demand levels. As rooftop solar PV panels and other 'behind the meter' energy resources become more prevalent, more elaborate modeling techniques for electricity demand would be worthy additions to analyses like this one.

Energy storage technologies, particularly batteries and electric vehicles, are also likely to significantly influence the growth and behavior of electricity systems. These technologies, along with generally growing electricity demand through electrification of non-electric energy consumption behaviors, will likely mean that some of the surplus electricity generated by the larger wind and solar PV infrastructure deployments tested above (2.15) could be harnessed rather than wasted through curtailment. At present, if too much electricity is fed into the grid by wind and solar PV generators, they may be instructed to curtail their generation so as not endanger other grid infrastructure through overloading. This is counterproductive for a number of reasons. For example, curtailed wind and solar PV electricity reduces the economic competitiveness of these energy resources and reduces the use of low-carbon and carbonless electricity generators. Energy storage technologies can absorb excess electricity at times of peak generation and help redistribute energy back into the grid during times of peak load. These devices would improve the efficacy of wind turbines and solar PV panels in meeting load and could reduce the amount of total nameplate generation capacity needed to fulfill electricity demands. This would, in turn, reduce the landscape impacts of electricity systems as a whole.

We have elected not to incorporate energy storage in this work as we feel it would significantly extend the scope of the work, add substantial modeling complexity, and stray from the paper's core purpose of assessing SEGs[5]. Instead, we feel this paper best serves as an enabler of further modeling and analysis in more focused areas, particularly power systems analysis, by grid operators, regulators, or other relevant stakeholders. Modeling of energy storage in this paper would entail making additional assumptions about future electricity load patterns, electric vehicle adoption, and

[5]Vermont's SEGs are technology agnostic and make no mention of energy storage technologies. Given the potential of energy storage devices in supporting the deployment and utilization of wind and solar PV generation resources, it is possible that energy storage capacity requirements may be included in future SEGs in Vermont and elsewhere.

interstate electricity trade. In addition, were large quantities of energy source capacity added to the grid, it is possible that their introduction would introduce a range of grid operation impacts across both the bulk transmission grid and local distribution lines. These topics represent significant additional work and their inclusion in this paper would further complicate the presentation of the scenarios tested which are already multifaceted with respect to infrastructure type, distribution, land area impacts, and performance relative to load.

We have also elected not to undertake explicit mathematical optimization analyses in this paper for similar reasons. As with the energy storage case, introducing optimization methods to the suite of test scenarios represents a significant extension of this paper's scope. Identifying optimal placements of new wind and solar PV infrastructure to meet SEGs with respect to one or more geospatial parameters, the electric grid, economic criteria, or other constraints is a worthy task, but one which can easily stand on its own in a separate paper. We believe this paper's outcomes and methods can be used to facilitate and more richly inform these efforts, particularly those undertaken by RTOs and ISOs. Specifically, we also believe that optimization with respect to certain parameters (e.g. maximizing electricity generation) could lead to overfitted solutions that are unlikely to be feasible to implement. For example, if a strictly optimal solar PV panel deployment were identified, the resulting infrastructure placements would fully saturate the 3km by 3km grid boxes that have the global maximum mean annual solar PV electricity generation potential and leave all other grid boxes unaltered, even those with only marginally inferior sunlight resources.

2.7 Conclusion

Deployment of renewable, low-carbon energy resources like wind and solar PV is already well underway in many parts of the world due to concerns over climate change, environmental and human health, and energy security. Governments are ratifying increasingly stringent SEGs to accelerate this process. Decarbonizing the electric grid and other energy demands through electrification will require orders of magnitude more wind and solar PV infrastructure to be installed, Understanding how distributed, intermittent electricity generators will impact the landscape and the grid is essential for streamlining the wind and solar PV implementation process.

This paper translates SEGs ratified by governments into a portfolio of specific, SEG-compliant wind and solar PV configurations and uses the state of Vermont as a case study. Each of the four SEGs examined can be achieved by wind and solar PV infrastructure configurations that directly occupy less than 1% of the state's land area. Vermont electricity demand was most effectively met by infrastructure configurations that prioritize electricity generation over other siting criteria. Configurations that relied solely on solar PV tended to perform least effectively versus electricity demand patterns and occupy the most land, while wind-only configurations were only marginally less effective in meeting demand than mixed configurations reflecting the state's current wind and solar PV infrastructure ratios. Diminishing returns in electricity demand satisfaction were observed across all configurations as they grew in total nameplate capacity, highlighting the inherent limitations of intermittent electricity generation resources.

Opportunities to extend and improve the efficacy of the REGS model include utilizing additional geospatial infrastructure siting criteria such as land cover type, viewshed impacts, access to existing transmission infrastructure, wildlife habitat and migration zone protection, and so on. These indirect landscape impacts are particularly important to capture for wind energy since the direct land area footprint of wind turbines per MW_{AC} of generation capacity is minuscule as compared to solar PV panels. Incorporating wind and solar PV infrastructure lifespan limits, energy storage technologies, and rooftop solar PV panel siting could also enhance the utility of modeling results and provide more information to electric grid stakeholders of all types.

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Chapter 3: Assessing the landscape-scale impacts of meeting statutory energy goals

Abstract

Energy policies that call for substantial or complete electricity system decarbonization infer the siting and installation of large amounts of new low-carbon energy infrastructure, particularly wind turbines and solar panels. Policy-compliant wind and solar infrastructure configurations will result in substantial land use and land cover changes, visual and sonic landscape disruption, and other environmental impacts, often in areas which do not currently host energy infrastructure. Local opposition to low carbon energy infrastructure siting due to these impacts can delay or even halt energy system decarbonization programs and, in turn, impede climate change mitigation efforts. While low carbon energy system models and modelling methods are prevalent, they rarely account for the land use impacts of energy infrastructure configurations or consider landscape criteria when selecting sites for new energy infrastructure. This paper presents methods for modeling the implied infrastructure requirements of energy policies and capturing their land area and land cover change impacts. Infrastructure siting is guided by user-defined site preferences and a diverse range of publicly-available datasets. These methods are demonstrated for the state of Vermont, home to strong energy decarbonization targets and a cherished natural landscape. Across all three siting preference scenarios tested, Vermont's 2035 renewable energy goal are shown to be achievable using well under 1% of the state's land area. These infrastructure and landscape impact pathway methods can be applied to regions throughout North America to inform energy system

stakeholders, policy makers, and local communities when deliberating over energy policy implementation plans. With tangible, scientifically grounded information in hand, these stakeholders can move beyond disagreements over hypothetical solutions and work towards actionable energy system decarbonization plans.

3.1 Introduction

Deployment of renewable energy sources, particularly wind turbines and solar photovoltaic (PV) panels, is accelerating worldwide thanks to a suite of social, environmental and economic factors including climate change, evolving consumer preferences, more stringent statutory energy goal (SEG) requirements, and financial considerations (Zervos & Adib, 2019). Combined, these factors are accelerating the pace of decarbonzation. SEGs in the United States and elsewhere, particularly those applicable to the electricity generation sector, are being strengthened and deadlines foreshortened in response to recent warnings from the Intergovernmental Panel on Climate Change (IPCC) and the increased frequency of extreme weather events (Intergovernmental Panel on Climate Change, 2018). Decarbonization of the electric grid represents the fulcrum of the wider decarbonization process both because replacement energy sources are readily available and because the successful decarbonization of the electric grid may facilitate other energy sectors like transportation and heating to decarbonize through electrification.

Large deployments of new electricity generation infrastructure are already having profound impacts on the electric grid (Denholm et al., 2015; Martinot, 2016). Changes to electric grid operation, reliability, resilience, and economics under high renewable energy penetration scenarios are all active areas of research. Existing fossil fuel-based energy systems occupy substantial amounts of land and indirectly impact adjoining lands in a variety of ways (Fthenakis & Kim, 2009). Land use and land cover (LULC) change impacts of large, SEG-compliant wind and solar PV infrastructure deployments have been less thoroughly addressed (see Dale et al., 2011; Ingerson, 2013). Although transitioning away from predominantly fossil fuel-based energy systems into low-carbon energy systems will alter which parts of the landscape are impacted, aggregate land cover impacts are likely to remain substantial (van Vuuren et al., 2017). Energy infrastructure development can disrupt human settlement patterns and natural habitats, visually or sonically impair the scenic or acoustic landscapes, or run afoul of cultural and indigenous land values (Tengberg et al., 2012; Wolsink, 2018). More broadly, energy infrastructure deployments could drive increased competition for land with incumbent land uses (e.g agriculture, forestry) and other development patterns (e.g. housing, industry), particularly in regions with more ambitious SEGs (Bazilian et al., 2011; Ringler et al., 2013). Land development for energy production is constrained by both strict physical landscape barriers (e.g. lakes, rivers, and wetlands), policy-imposed restrictions (e.g. floodplains, steep slopes), and existing infrastructure which is impractical to remove or modify (e.g. airports, railways, transmission lines, etc.). We contend that modeling the land area impacts of electric grid decarbonization as part of renewable energy infrastructure planning and deployment processes are crucial for achieving SEGs in a timely, equitable fashion.

Achieving electric grid decarbonization through wind and solar PV infrastructure deployment, particularly on the short time scales demanded by climate change and SEGs, will require planning, cooperation, and coordination among all electricity system stakeholders, including electric grid operators, existing electricity generators, electric utilities, local, regional, and national governments, businesses, land owners, and private citizens. Each of these stakeholders will have different preferences for which types of infrastructure should be used, where the infrastructure should be located, which land cover types should be prioritized for preservation, and who should control these decision-making processes. Developing a consensus pathway(s) for delivering a SEG-compliant electric grid must therefore place these stakeholder considerations at the center of the energy planning process. Failure to consider the full range of stakeholder perspectives could slow or derail decarbonization efforts. Moreover, in the absence of feasible, SEG-compatible pathways to compare and contrast, deliberations among energy system stakeholders and planning authorities are prone to remain firmly in the realm of the hypothetical.

A large portion of the contemporary literature concerning the landscape impacts of wind and solar PV infrastructure focuses either on impacts of individual infrastructure installations (e.g. the visual impacts of a proposed wind turbine installation (Tsoutsos et al., 2009)) or micro-scale land/infrastructure interactions (e.g. co-location of solar PV panels among agricultural lands (Dupraz et al., 2011)). Other studies in this area estimate aggregate land area needs for large deployments of wind and solar PV in general terms using weather conditions, land use parameterizations, and future energy requirements as model parameters (Arent et al., 2014; Shum, 2017).

This paper describes an approach to modeling the landscape-level impacts of large-scale wind and solar PV infrastructure deployments in pursuit of policy-driven electric grid decarbonization and illustrates how different priorities impact energy infrastructure needs, LULC change, and landscape aesthetics. We extend the Renewable Energy Growth Scenario (REGS) model (Thomas & Racherla, 2019) by identifying locations for wind and solar PV and quantifying associated land cover changes. The REGS model now also allows users to guide new energy infrastructure placements on the landscape by ranking site suitability criteria preferences using publicly available geospatial datasets. The aim of this work is to deliver scientifically-grounded, broadly understandable information to stakeholders and accelerate the development of achievable, agreeable, and equitable pathways.

3.2 Methods and Data

The REGS model was inspired by the work of Becker et al. (2014) and Siyal et al. (2015). A summary of the REGS model is provided below; readers are advised to consult Thomas and Racherla (2019) (Chapter 2) for a more complete accounting of the REGS model. In this paper we detail the development of a module for placing wind and solar PV infrastructure at spatially explicit locations based on user-specifies preferences. This enhancement enables the user to derive direct infrastructure deployment/land cover change relationships and reveals far more granular tradeoffs between potential wind and solar PV infrastructure deployment pathways.

The REGS model deploys clusters of fixed-angle ground-mounted solar PV panels (FAPV), two-axis sun-tracking solar PV panels (TPV), and industrial scale wind turbines on 60m by 60m (3600m^2) plots of land. In order to more fully explore the relationship between wind and solar PV infrastructure deployment and landscape change, several modifications to the REGS model were necessary. The primary change was to create a second infrastructure siting domain with a 30m resolution[1]. By assigning new infrastructure to specific locations, rather than just a general area, direct LULC changes can be quantified and siting restrictions can be more realistically considered in the model. In turn, more detailed maps can be produced to communicate results more clearly.

Figure 3.1 provides a detailed overview of the REGS model. The user first specifies several modeling parameters including the ratio of new FAPV to TPV to wind turbine nameplate generation capacity, the site selection method, and the desired target infrastructure installation (in terms of nameplate generation capacity, land area requirements, or annual electricity generation). New wind and solar PV infrastructure can be sited using one of five methods: maximize generation, cluster near or spread away from existing infrastructure, landscape siting preferences, or random placement. New wind turbines and solar PV panel clusters are sited one at a time based on weighted random number draws. At the start of each iteration, the infrastructure type is selected based on the user-defined infrastructure ratios. Next, site selection is carried out in a two-step process. New infrastructure is first allocated to a 3km by 3km cell using a weighted random number draw. Weights for each eligible cell are determined by the criteria in question (e.g higher quality wind resource areas will be preferentially chosen in the maximum generation siting method). A specific plot of land is then chosen in the 30m by 30m resolution domain (with each infrastructure placement occupying four cells worth of land) based on a final weighted random number draw. This process is repeated one wind turbine or solar PV panel cluster at a time until the desired model target has been met.

The REGS model uses a fixed parameter (Ong et al., 2013) to relate nameplate capacity to land area for each infrastructure type which is drawn from. All FAPV infrastructure is assumed to occupy land at a rate 51.67 W_{DC} per m^2 and all TPV infrastructure is assumed to occupy land at a rate[2] of 26.67 W_{DC} per m^2. Generic $3MW_{AC}$, 80m hub height wind turbines are deployed for new wind energy installations. Electricity generation estimates are developed using five years of hourly, 3km resolution weather data provided by James et al. (2017). Wind turbines, unlike solar PV panels, must be separated from one another to ensure safe operation and limit the impact of neighboring wind turbines on each other's electricity generation potential (González-Longatt et al., 2012). A 1000m radius wind turbine siting restriction[3] is enforced around all existing and new wind turbines.

Siting of new energy infrastructure is constrained by a range of physical, legislative,

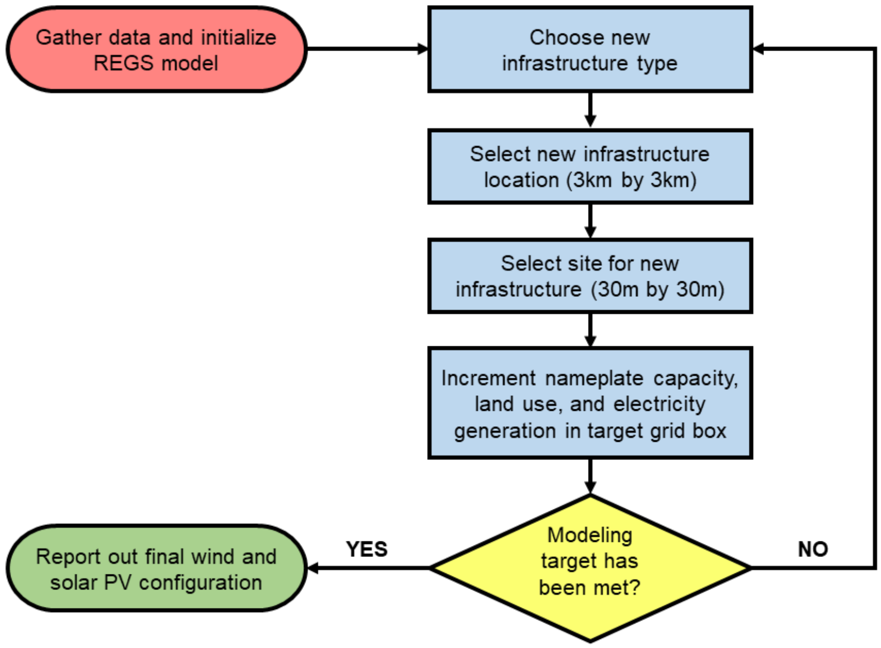

Figure 3.1: REGS model flowchart

and societal barriers. A wide range of geospatial datasets can be used to parameterize the infrastructure siting process. With one exception, all of the datasets used in this analysis are drawn from publicly available databases. The National Land Cover Database (NLCD; Multi-Resolution Land Characteristics Consortium, 2016) serves as the base data layer for the model. It and the United States Geological Survey (USGS) National Elevation Dataset (NED), both of which provide nationwide coverage, establish the foundation for the core geospatial analyses in the REGS model. Numerous other federal, state, and local datasets can be used to represent siting priorities and restrictions. ArcGIS Pro v2.4.2 was used for all geospatial data processing in this paper.

The modeling effort described in this paper employs the 2016 edition of the NLCD. The NLCD uses a set of 20 land cover classes to categorize the landscape. Two key alterations were made to the NLCD. First, the NLCD dataset was reprojected to align with the weather data. Second, a set of four new land cover classes were created: 1) rooftop solar PV panels[4], 2) FAPV panels, 3) two-axis sun-tracking solar PV (TPV) panels, and 4) wind turbines.

The siting of wind turbines can be controversial, due in part to their visibility on the landscape. Delineating potential impacts is crucial for informing siting decisions. The visual impacts of wind turbines were derived through viewshed analysis (Carver & Markieta, 2012; Klouček et al., 2015). Viewsheds were calculated using the Viewshed 2 geoprocessing tool which requires three inputs: 1) an observer point, 2) a digital elevation model, and 3) a desired outer radius for analysis. The Viewshed 2 tool draws lines of sight from an observer point to the surrounding landscape and then delineates visible areas based on these sight lines and the topographic variation between the observer point and each location on the landscape. The observer points are set at the tip of a wind turbine blade at full vertical extension and are thus are fixed at 130m above the earth's surface. The USGS NED was used to define the digital elevation model and viewsheds were modeled out to a radius of 18 kilometers (approximately 11 miles; Sullivan et al., 2012).

3.3 Vermont Case Study

The state of Vermont presents a unique setting for examining the interactions of energy policy and LULC change thanks to its combination of strong SEGs, highly valued rural landscape, low population density, and robust land use planning regulations. Vermont's current SEGs were established by the State Legislature's 2016 Comprehensive Energy Plan (CEP; Vermont Department of Public Service, 2016). The two principal policy goals contained in the CEP are to reduce total per capita energy consumption by at least 33% by the year 2050 and meet at least

90% of energy demand in 2050 with renewable energy sources. Vermont consumed 128.7 trillion British Thermal Units (BTU) of energy[5] in 2016, equivalent to 37.7 TWh of electrical energy, with total in-state renewable electricity generation meeting just 2.5 TWh of that energy demand (US Energy Information Agency, 2018). The CEP therefore implicitly calls for an increase in wind and solar PV infrastructure installations sufficient to provide roughly 20 TWh of energy per year (an eight-fold increase on today) assuming energy efficiency targets are met.

Vermont's present solar PV infrastructure is distributed widely throughout the state, as seen in Figure 3.2A, with a moderate bias towards developed areas and larger population centers. In January 2019, renewable energy infrastructure occupied just 0.02% of Vermont land (5 km^2) consisting of 316.3 MW_{DC} of FAPV (of which 102 MW_{DC} was roof-mounted), 23.5 MW_{DC} of TPV, and 149.0 MW of wind turbine generation capacity (Energy Action Network, 2019). Vermont's current wind turbine infrastructure is comprised of 67 individual wind turbines in four clusters, three in northern Vermont and one in southern Vermont (see Figures 3.2A and 3.3). In each case, the wind turbines have been sited on locally high terrain which provides access to the highest mean wind speeds while also rendering them visible across a greater extent of the landscape. This tradeoff between wind energy returns and infrastructure visibility will feature prominently in the scenario analysis.

Vermont has a diverse, largely undeveloped landscape consisting of 24,160 km^2 of land and 985 km^2 of open water. The dominant landscape features in Vermont are the densely forested Green Mountains that run north/south through the center of the state (see Figure 3.2B). Vermont was heavily logged in the 19th century as the state's population, agricultural production, and industrial ambitions grew (Bushnell, 2018). Reforestation and preservation efforts began in earnest in the early 20th century and today approximately 73% of Vermont is now covered by a mixture of deciduous and evergreen forests. To the west of the Green Mountains, the eastern shore of Lake Champlain and its surrounding valley is home to the state's largest population center of Burlington (Chittenden County) and the majority of the state's agricultural lands (Addison County and Franklin County). Along Vermont's eastern border lies the Connecticut River valley, home to a mixture of agricultural and forested lands. In total, agricultural lands (pastures, hay fields, and cultivated crops) account for roughly 13% of Vermont's total land area. Developed lands account for just 6% of Vermont land. Vermont's forests and farmlands represent the vast majority of the state's land area and give rise to its 'working landscape'. Forestry and agriculture are two of Vermont's main industries and significantly contribute to a third main industry, tourism and recreation. They also form much of the state's identity to locals and visitors alike. Preserving Vermont's working landscape and the industries/policies that support it is therefore a key consideration when contemplating the deployment of new energy infrastructure.

The degree to which Vermont's land use development laws foster or inhibit renewable energy deployment will directly influence how successfully Vermont's SEGs are met and which parts of the landscape are impacted most. There are three main state-level laws which govern the development of land for renewable energy purposes in Vermont: Act 250, Section 248, and Act 174 (Vermont Legislature, 1969, 1970, 2016). Act 250 (Land Use and Development Act) is Vermont's all-purpose land development law which stipulates that all land developments larger than 40,000 m^2 and/or above 762 meters (2,500 ft) in elevation must be reviewed and permitted by one of nine District Environmental Commissions. Act 250 contains ten permitting criteria concerning air pollution, watershed disruption, traffic, scenic resources, and other potential impacts. Section 248 governs the development of new energy infrastructure, renewable or otherwise. The Vermont Public Utility Commission issues Certificates

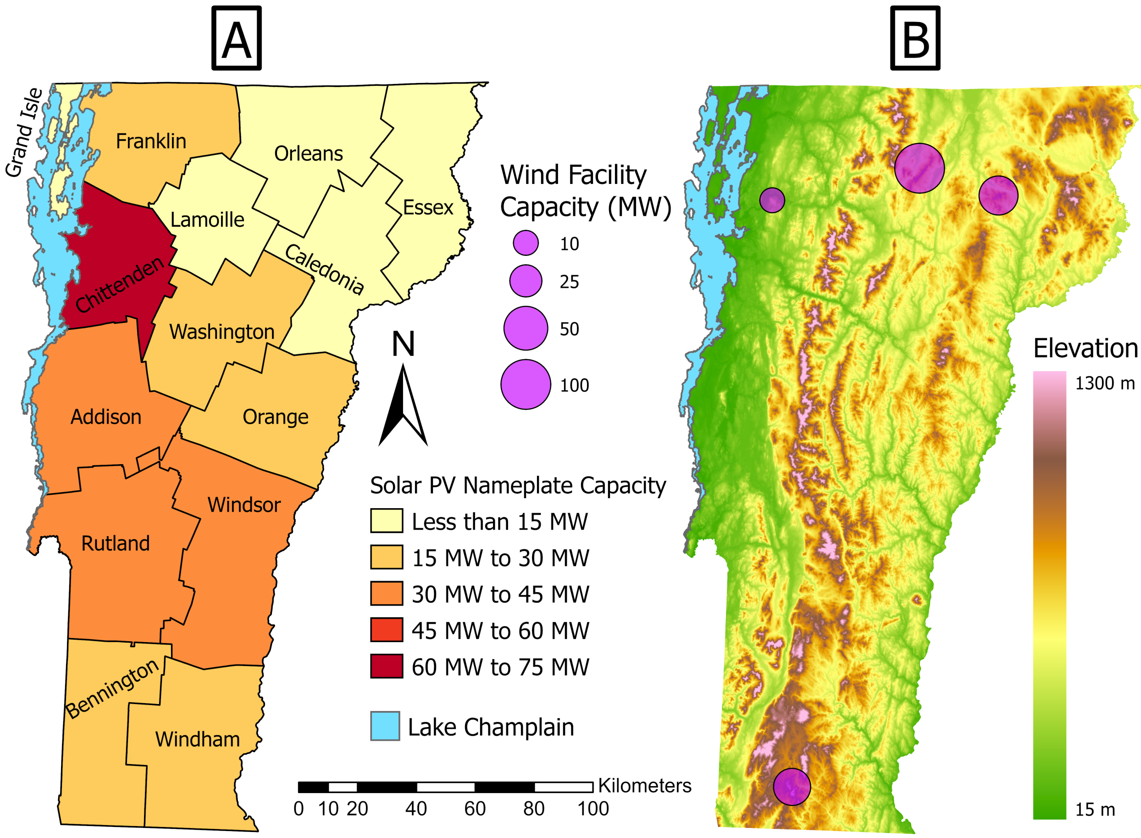

Figure 3.2: A: Installed solar PV panel nameplate capacity by county as of January 2019. B: Vermont elevation and wind turbine installations as of January 2019.

of Public Good (CPGs) to projects that meet Section 248 criteria and uses Act 250 criteria as part of the adjudication process. Because of this legal environment, proposed renewable energy projects must navigate a substantial oversight and scrutiny process across multiple governmental bodies and jurisdictions. Act 174, passed in 2016, endeavors to streamline energy development proposal decisions by granting "substantial deference" in energy-related development decisions to municipalities that develop and publish regionally approved energy plans. In theory, this means towns will proactively identify preferred renewable energy development areas, infrastructure types, installations sizes, and establish local targets as an appropriate share of Vermont's statewide SEGs. In turn, prospective energy developers would know in

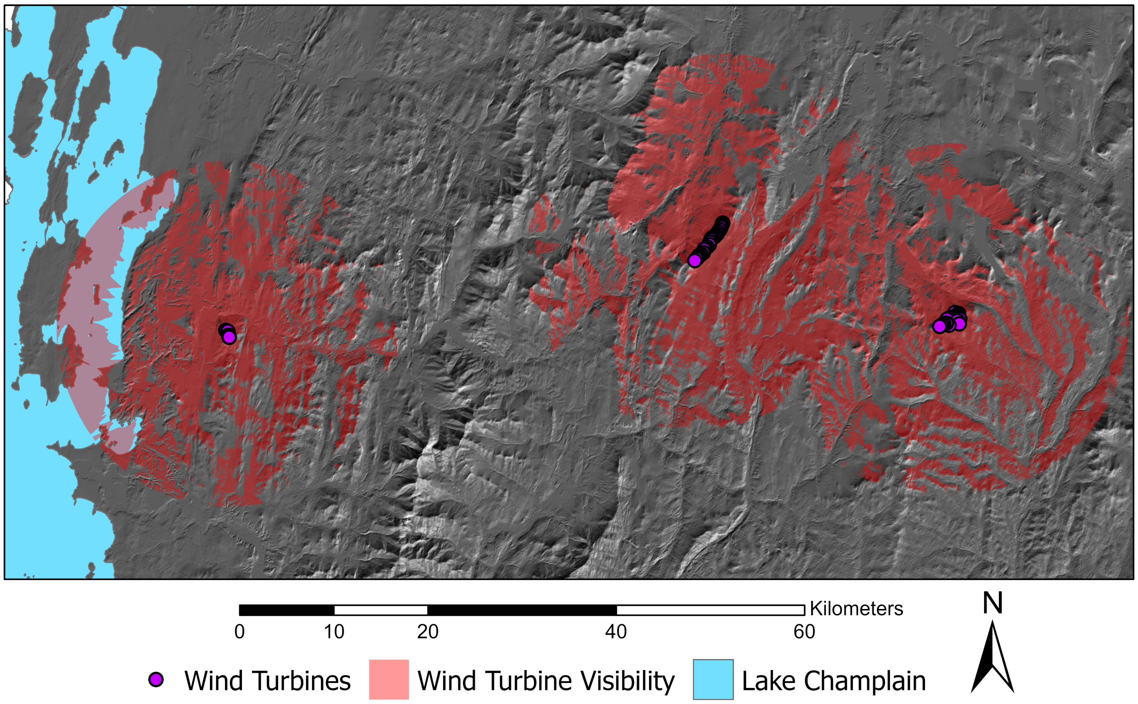

Figure 3.3: Estimated viewshed for three northern Vermont wind turbine installations.

advance how likely a proposed development is to be granted permission under Act 250 and Section 248 reviews. At the time of writing, just 46 out of 255 of municipalities have developed Act 174 compliant energy plans[6]. Whether this has led to permit streamlining remain unknown at this time.

In order to explore the potential tradeoffs in infrastructure needs, land area requirements, land cover changes, and distributions of infrastructure throughout the state of Vermont, we developed three scenarios for examination in the REGS model. Each scenario features a target[7] of 12 TWh of wind and solar PV electricity generation per year. For each scenario, three trials are conducted: only new wind turbines, only new solar PV, and a combination of wind turbines and solar PV panels proportional to Vermont's existing wind and solar PV nameplate capacities. As of January 2019, FAPV, TPV, and wind turbine nameplate capacities are 64.7%, 4.80%, and 30.50%, respectively. For the solar PV-only scenarios, the January 2019 ratio of

Table 3.1: Vermont geospatial dataset summary

Data category	Dataset name	Dataset source organization	Siting restriction or score?
Population	E911 Site Locations	VCGI	Score
Protected land	Protected Lands Database	VCGI/Various	Restriction
Protected land	VT Act 174 Conservation Design Layers	VCGI/VT ANR	Score
Roads and rails	Rail Lines	VCGI/VTRANS	Restriction
Roads and rails	Road Centerlines	VCGI/VTRANS	Restriction
Roads and rails	Road Widths 2018	VCGI/VTRANS	Restriction
Structures and developed land	E911 Footprints	VCGI	Restriction
Structures and developed land	EPA Region 1 Superfund NPL Site Boundaries	EPA	Restriction
Transmission lines	VT Transmission Line Right-of-Ways[8]	VELCO	Both
Transmission lines	GMP Sub-transmission lines and distribution lines	VCGI/GMP	Score
Transmission lines	VEC Sub-transmission lines and distribution lines	VCGI/VEC	Score
Water/wetlands	Lake Buffers 100ft and 250ft	VT ANR	Restriction
Water/wetlands	River Corridors	VCGI/VT ANR	Restriction
Water/wetlands	River Corridor Easements	VCGI/VT ANR	Restriction
Water/wetlands	Small stream 50ft setbacks	VCGI/VT ANR	Restriction
Wildlife	Deer Wintering Areas	VCGI/VT ANR	Score
Wildlife	Habitat Blocks and Wildlife Corridors	VCGI/VT ANR	Score
Wind and solar PV infrastructure	Renewable Energy Atlas	Energy Action Network	N/A

FAPV (93.06%) to TPV (6.94%) was used.

In addition to the NLCD and NED, Vermont-specific datasets were used to develop the three test scenarios (see Table 3.1). When combined, these data define where renewable energy infrastructure is impractical or impossible (i.e. restricted). They also enable users to identify which types of sites are most and least ideal for development, information which is converted into site scores for use within the REGS model siting process described above. For example, development is restricted in the REGS model on any parcel of land included in the Protected Areas Database 2.0 and the Protected Lands Database. Development is similarly restricted for sites underneath existing electricity transmission line corridors, but the proximity of eligible sites to these corridors can be used to score site quality in the model. Other examples of site scoring criteria include existing land use types and wildlife habitat information.

Scenario 1 seeks to preserve Vermont's working landscape by preventing infrastructure siting on forests and agricultural land cover classes. Wind turbines are preferentially sited away from high population density areas to reduce their impacts on human populations.

Scenario 2 considers the siting priorities of prospective energy developers. Desirable sites are modeled as those closest to (but not under) existing high-voltage transmission lines along with infrastructure-specific criteria. For solar PV, land with a south-facing aspect close to population centers is ideal. Areas with higher population densities are used as a proxy for target locations with better electricity distribution line access. Wind turbines are also preferentially sited away from population centers and on higher terrain in order to access the best wind resources.

Scenario 3 focuses exclusively on the visual impacts of wind and solar PV infrastructure on the landscape. In this scenario, solar PV infrastructure is located away from scenic highways and byways as defined by the Vermont Agency of Transportation. Wind turbines are sited solely according to their modeled viewshed impact and away from high population densities.

In addition to the three scenarios described above, there are also scenarios focused on maximizing energy returns for either wind or solar. One trial includes only wind turbine deployment and the other trial deploys both wind turbines and solar PV panels using the January 2019 infrastructure ratios as before. These reference scenarios are designed to draw distinctions between the land use needs and wind turbine visibility impacts of siting according to energy production returns as opposed to the landscape impact priorities which were the focus of the scenarios described above.

3.4 Results

Figure 3.4 shows where new wind and solar PV infrastructure can and cannot be sited in Vermont as determined by the suite of geospatial data shown in Table 3.1. Land use restrictions preclude renewable energy infrastructure siting on approximately 10,459 km^2 (43.3%) of Vermont's landscape. While solar PV panels can be sited on the remaining 13,701 km^2 (56.7%) of Vermont land, the same is not true for wind turbines. Due to FAA airspace restrictions near airports and in military flight training corridors, only 10,893 km^2 (45.1%) of Vermont is suitable for siting wind turbines.

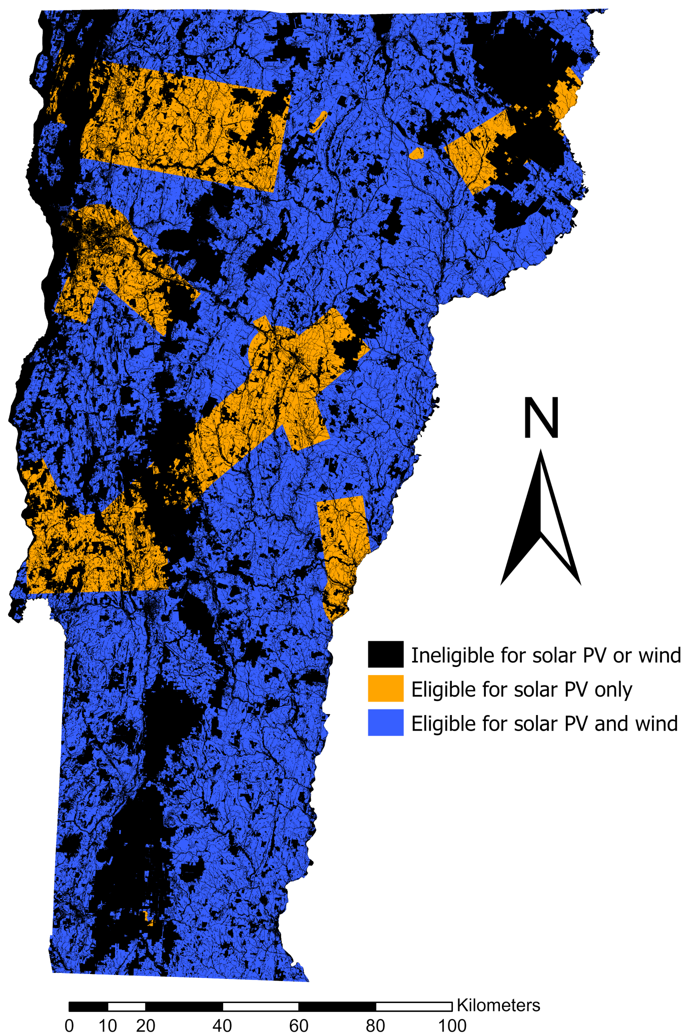

Figure 3.4: Modeled wind and solar PV infrastructure siting restrictions

Figure 3.5 reveals how siting eligibility matches Vermont electricity generation potential. In this figure, wind and solar resource quality increases from left to right. Vermont's best wind resources occur in locations with little to no eligible land. Solar resources are similarly constrained, albeit less severely. The highest mean wind speed location in Vermont is 250% faster than the lowest mean wind speed location while the sunniest areas are only about 25% sunnier than the cloudiest locations. Electricity generation from wind turbines is therefore far more sensitive to siting location than solar PV generation and is also more significantly constrained by siting restrictions.

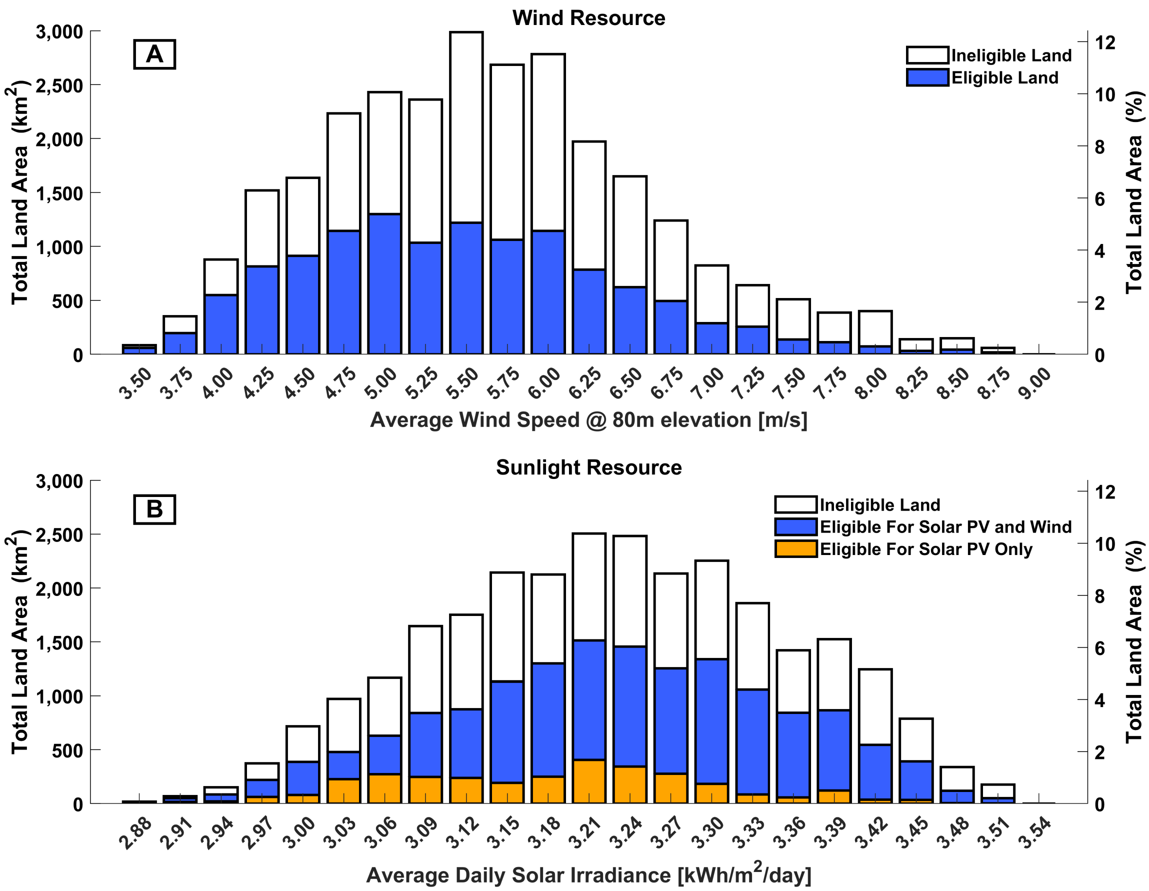

Figure 3.5: Distribution of eligible and ineligible infrastructure sites versus wind and solar resource quality

Table 3.2 summarizes the infrastructure and land area requirements under each scenario. 100% wind turbine deployments required the least new nameplate generation capacity to reach the 12 TWh per year target (approx. 4.8 GW_{AC}) while 100% solar PV panel deployments required the most new nameplate generation capacity (7.6 to 7.9 GW_{DC}). Total infrastructure requirements vary only slightly across the three test scenarios per infrastructure mix. Land area impacts mirror nameplate capacity requirements since nameplate capacity per unit area ratios are held fixed in the REGS model. The land area required to meet Vermont's 2035 SEG with only wind and solar PV infrastructure installations is less than 1% of the state across all scenarios. The land cover restrictions imposed in Scenario 1 did not lead to an appreciable increase in infrastructure and land area requirements when compared to Scenarios 2 and 3. This suggests that the distribution of forested and agricultural lands in Vermont is not appreciably biased towards or away from high- or low-quality generation potential areas as compared to other land cover types. Total visual landscape disruption from wind turbines increases by at least seven-fold for mixed infrastructure trials and ten-fold for 100% wind trials as compared to the initial visual impact conditions modeled for January 2019. Visual impacts on human populations were highest in Scenario 1 and lowest in Scenario 3, though only by narrow margins. Visual impacts on protected lands were highest in Scenario 2 and noticeably lower in Scenario 1.

Figure 3.6 shows that while each scenario resulted in similar total land area requirements for achieving SEGs, the land cover change impacts differed substantially. Scenario 1 stands out due to the strict preservation of forest and agricultural land, shifting development to other land cover classes in much higher proportions than in Scenarios 2 and 3. Scenarios 2 and 3 have smaller but still noteworthy differences. Scenario 2 lost more grassland, more shrub/scrub land, more forested land, and less agricultural land as compared to Scenario 3. If more ambitious SEGs were to be modeled using this suite of scenario parameterizations, it is possible that the small variations in infrastructure needs, land area needs, and visual impacts could widen proportionately as areas with particular land cover and generation potential combinations become more saturated.

Figures 3.7 and 3.8 show[9] where wind turbines and solar PV panels, respectively,

Table 3.2: Landscape siting scenario results: infrastructure requirements, land area coverage, and visual impacts

	Scenario 1 100% Wind	Scenario 1 Current Mix	Scenario 1 100% Solar PV	Scenario 2 100% Wind	Scenario 2 Current Mix	Scenario 2 100% Solar PV	Scenario 3 100% Wind	Scenario 3 Current Mix	Scenario 3 100% Solar PV
New 3MW wind turbines	1,605	662	–	1,591	658	–	1,595	673	–
New wind turbine capacity (GW_{AC})	4.815	1.986	–	4.773	1.974	–	4.785	2.019	–
New 300W FAPV panels	–	14,021,920	23,668,500	–	13,946,280	23,623,240	–	14,276,740	24,481,940
New FAPV capacity (GW_{DC})	–	4.207	7.101	–	4.184	7.087	–	4.283	7.345
New 6kW TPV units	–	52,016	88,256	–	51,712	88,096	–	52,960	91,296
New TPV capacity (GW_{DC})	–	0.312	0.530	–	0.310	0.529	–	0.317	0.548
Total New Land Area (km^2)	5.778	95.504	157.288	5.728	94.982	156.989	5.742	97.236	162.695
Vermont population with wind turbine visibility (%)	83.616	61.151	8.081	82.702	71.522	8.081	80.987	68.109	8.081
Vermont protected land with wind turbine visibility (%)	73.606	53.206	7.027	73.942	59.797	7.027	75.992	58.901	7.027

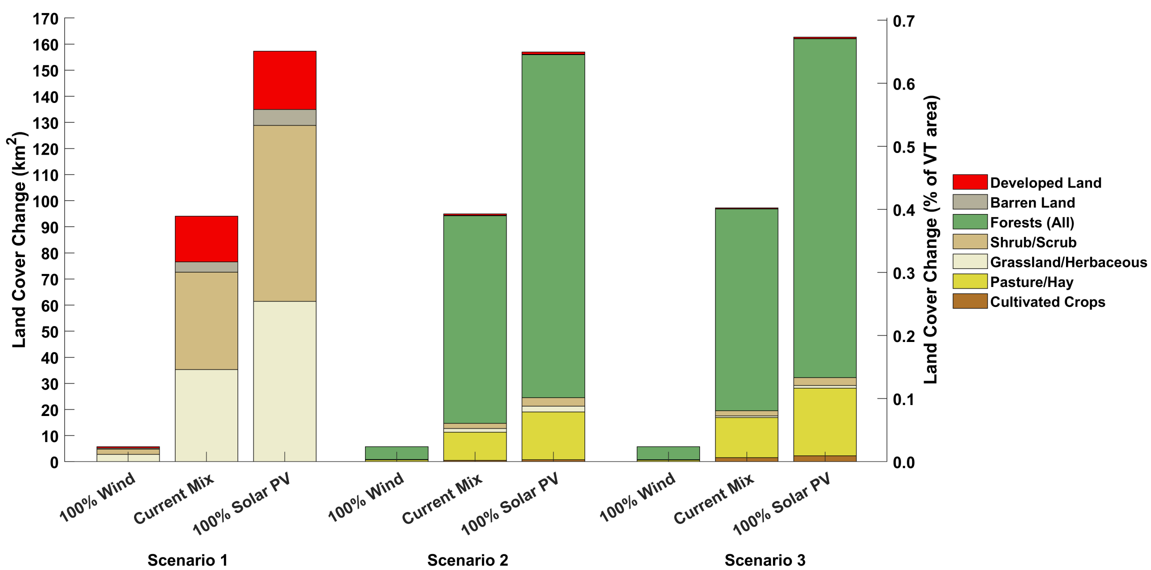

Figure 3.6: Total LULC displacement for Scenarios 1, 2, and 3

are sited on the landscape across all nine siting strategy and infrastructure mix permutations. 100% wind or solar PV infrastructure trials are shown *entirely* within subplots D, E, or F. Mixed infrastructure trials are formed by the combination of wind turbines and solar PV panels mapped in subplots A, B or C. For example, Scenario 1's mixed infrastructure configuration trial is comprised of the infrastructure shown in Figures 3.7A *and* 3.8A.

Scenario 1's land cover change limitations resulted in largely scattered infrastructure configurations for both wind and solar PV (see figures 3.7A). Localized clusters of solar PV infrastructure developed in some higher population areas (e.g. central Chittenden County and southern Bennington County) where larger concentrations of existing developed land are available for siting. Wind turbines were predominantly sited in southern Vermont (Rutland and Windsor counties) and the Northeast Kingdom (i.e. Caledonia, Orleans, and Essex counties).

Scenario 2's focus on siting near transmission lines resulted in somewhat similar infrastructure distributions as compared to Scenario 1. Airspace restrictions in central and western Vermont (see figure 3.4) overlap with several transmission line corridors and create sharp divides between areas with relatively high wind turbine densities (e.g. northern Washington County) and areas with little to no wind turbine siting (e.g. southern Washington County). Solar PV panels follow a similar pattern but are able to access sites in close proximity to transmission lines that could not be accessed by wind turbines (e.g. southern Franklin County).

Scenario 3's focus on visual impact mitigation produced similar wind turbine configurations but dramatically different solar PV panel configurations as compared to Scenarios 1 and 2. Solar PV panel siting was almost exclusively confined to northern and central Vermont where none of the State's scenic highways and byways are located. Eastern Franklin County received over half of the state's solar PV panels in Scenario 3 with the remainder being sited in the eastern foothills of the Green Mountains. Scenario 3's solar PV panel requirements were slightly higher than those Scenario 1 and 2 thanks to the relative cloudiness of Franklin County versus the rest of Vermont. Scenario 3's wind turbine configurations are quite similar to those from Scenario 2, suggesting that while the visibility-based siting strategy did reduce overall visual impacts slightly, it did not significantly change how many wind turbines were needed or where they would be sited.

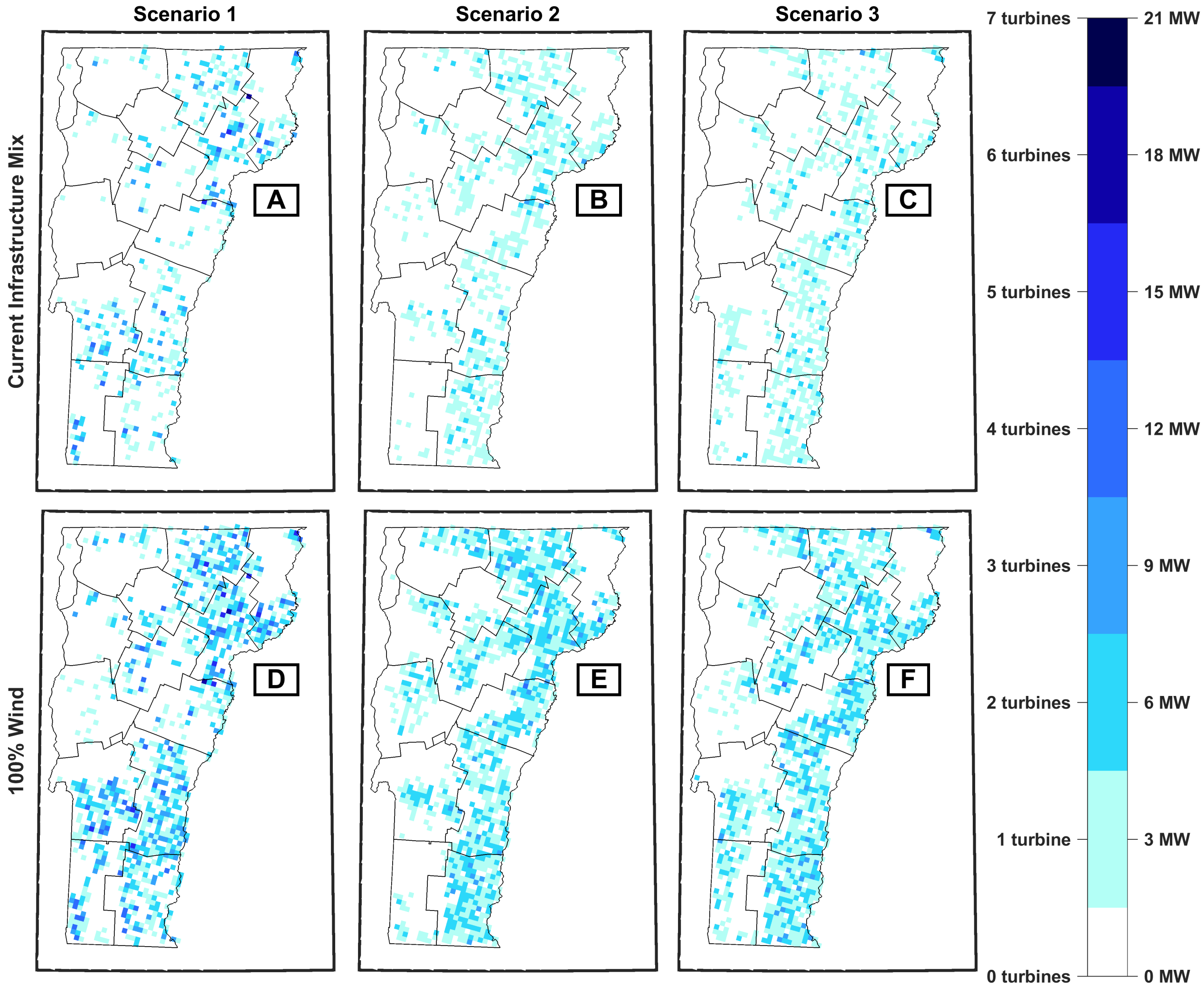

Figure 3.7: Maps of new wind turbine placements for the 100% wind and current infrastructure mix scenarios. Note that each pixel shown is 3km by 3km in size.

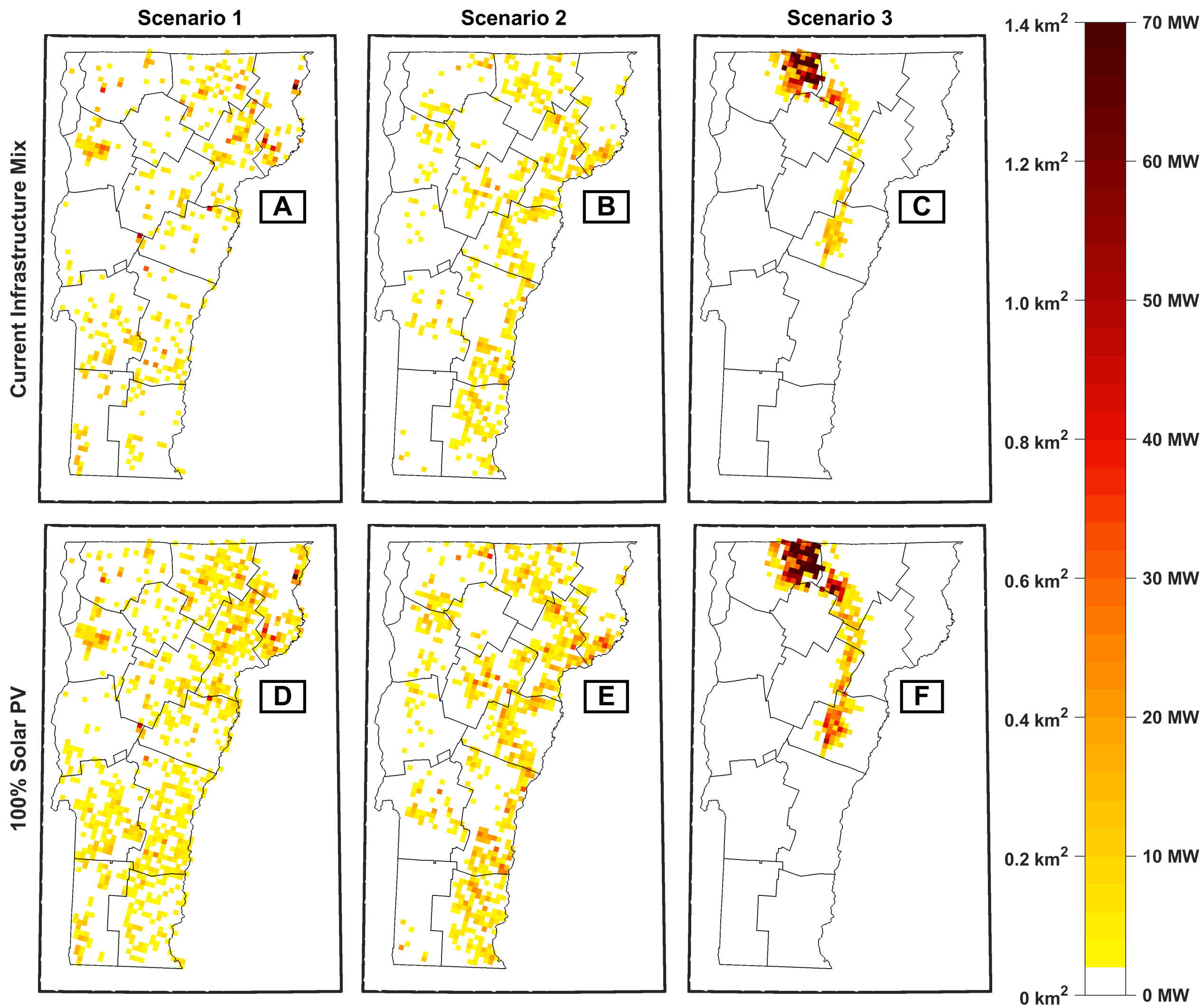

Figure 3.8: Maps of new solar PV panel placements for the 100% solar PV and current infrastructure mix scenarios. Note that each pixel shown is 3km by 3km in size.

Table 3.3 compares Scenario 3's mixed infrastructure and 100% wind trials to a maximum generation siting strategy scenario. These data illustrate the benefits and drawbacks of generation-focused and visibility-focused siting strategies when meeting ambitious SEGs with wind and solar PV infrastructure. Across both infrastructure mixes, the maximum generation scenario required substantially fewer wind turbines and solar PV panels. As a consequence, the associated land area requirements and visibility impacts were reduced. Wind turbine requirements were nearly halved in the 100% wind trials and total infrastructure needs were cut by nearly 30% in the mixed infrastructure trials. Wind turbine visibility impacts were also substantially reduced in both maximum generation trials but to varying degrees. Visibility impacts for protected lands decreased by a third while visibility impacts for human populations dropped by 50% or more.

Figure 3.9 reveals the cause of the uneven visibility impact reductions. The maximum generation trials aggressively target new wind turbines towards any eligible plot of land along the spine of the Green Mountains where mean wind speeds are strongest. Even though these areas are highly visible to the surrounding landscape, the large electricity generation returns they yield reduce the total number of wind turbines required to meet the SEG. This, plus the tight clustering of the wind turbines means that visibility impacts are more concentrated in central and southeastern Vermont and almost non-existent elsewhere. Visibility impact reductions for protected lands in these trials, while appreciable, are not as dramatic as those for human populations due to the prevalence of protected lands in and around the Green Mountains. Solar PV panels are spread fairly evenly throughout Vermont in the maximum generation trials with a slight bias towards the eastern slopes of the Green Mountains. The sunlight resource is slightly stronger there due to a climatological rain shadow created by the Green Mountains.

Table 3.3: Maximum generation siting results vis-à-vis Scenario 3 results

	Scenario 3 100% Wind	Max. Gen. 100% Wind	Scenario 3 Current Mix	Max. Gen. Current Mix
New 3MW wind turbines	1595	903	673	477
New wind turbine capacity (GW_{AC})	4.785	2.709	2.019	1.431
New 300W FAPV panels	–	–	14,276,740	10,097,940
New FAPV capacity (GW_{DC})	–	–	4.283	3.029
New 6kW TPV units	–	–	52,960	37,456
New TPV capacity (GW_{DC})	–	–	0.318	0.225
Total New Land Area (km^2)	5.742	3.251	97.236	68.778
Vermont population with wind turbine visibility (%)	80.987	41.413	68.109	31.139
Vermont protected land with wind turbine visibility (%)	75.992	49.263	58.901	40.559

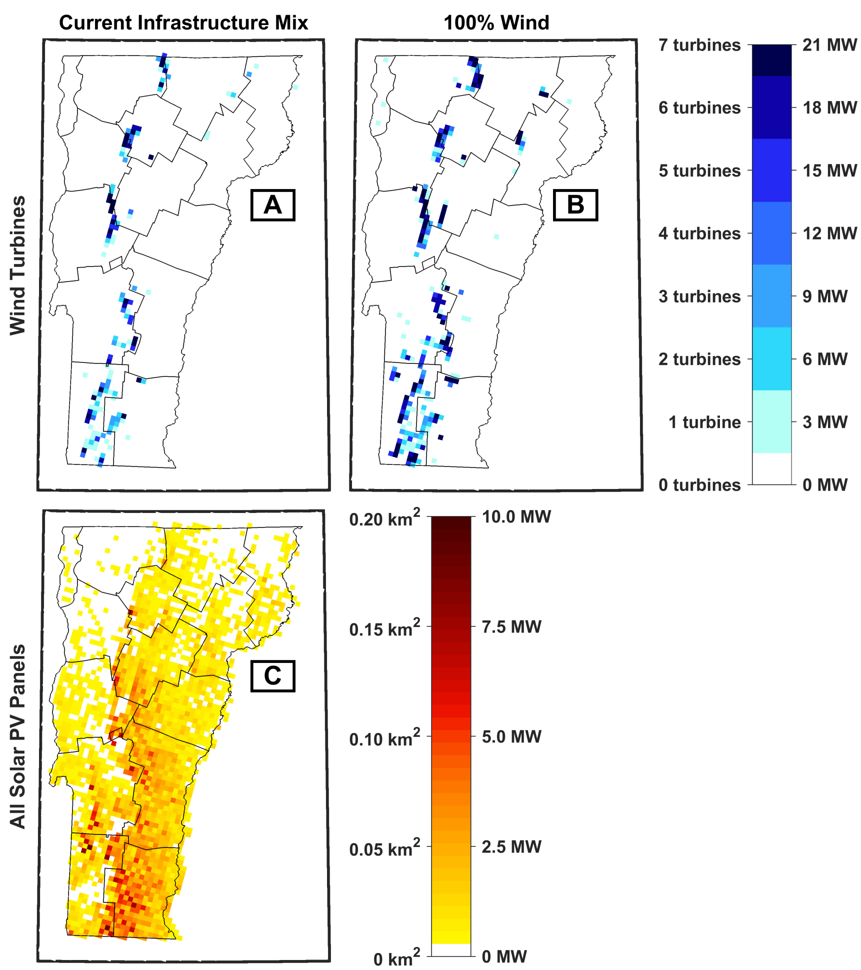

Figure 3.9: Maps of new wind turbine and solar PV panel placements in the maximum generation scenario

3.5 Discussion

These case study results provide insights on Vermont's situation but with lessons applicable to any region contemplating significant wind and solar PV infrastructure deployments. The fundamental dynamic captured in the scenarios is the tradeoff between direct impacts (i.e. LULC changes and their adjacent ramifications) and indirect landscape impacts (e.g. visual disruption, degradation of cultural ecosystem services, changes to place-based identity) when implementing SEGs. Solar PV panel deployment dictates the magnitude of total LULC impacts while wind turbine deployment dictates the visual landscape impacts. Though not captured by the REGS model, wind turbines typically induce larger LULC impacts than those caused by the wind turbines themselves (Denholm et al., 2009).

For regions like Vermont with adequate weather conditions and low ratios of energy demand to land area, the direct LULC change impacts of SEG-compatible wind and solar PV energy systems are relatively small. In regions where one or more of these factors varies, the aggregate LULC changes may increase rapidly. Despite the relatively low land use impacts of the Vermont pathways, visual impacts remained substantial even with a majority solar PV capacity infrastructure mix. While each pathway resulted in less than 1% of Vermont land area being developed for renewable energy, each scenario that included new wind turbine deployment resulted in at least a majority of the state's population and protected land area having wind turbine visibility. Maximum generation-focused deployments substantially mitigated this problem but in doing so concentrated new infrastructure deployments into a handful of areas.

The prevailing outcome of the Vermont case study is that there is no 'best' or 'correct' solution: each pathway has pros and cons. While the REGS model provides firm foundations to work from, the planning process still boils down to doing the hard work of compromise-building. The REGS model can be the starting point for deliberations among stakeholders but it must not be the only tool used in the energy system planning process.

There are several factors to consider that are not captured by the REGS model which are nonetheless important. These include infrastructure purchase and maintenance costs, rates of infrastructure deployment and replacement, rooftop solar PV adoption rates, and interactions with energy storage and transmission line investments. Each of these would be a valuable enhancement of the REGS model. Alternatively, the REGS model could be paired with other energy modeling programs that do include these elements but lack explicit modeling of land area requirements and siting preferences. Potential enhancements to the scenarios explored here could include explicit modeling of solar PV visual impacts (e.g. Chiabrando et al. (2009)), additional renewable energy infrastructure options (e.g. offshore wind turbines, biomass generators, anaerobic digesters), and county-by-county infrastructure allocation modeling. These enhancements could further improve the utility of the modeling results for stakeholders.

3.6 Conclusion

Tackling climate change by, in part, deploying wind and solar PV electricity generation infrastructure will reshape our relationship with the electric grid. The updated REGS model presented here develops wind and solar PV infrastructure deployment pathways that explicitly pair infrastructure configurations, electricity generation modeling, and land area needs. These pathways can be used as a basis for developing consensus among electricity system stakeholders and further, more detailed analyses of such deployments. To demonstrate the capabilities of the REGS model, a case study of the state of Vermont was conducted. While Vermont has aggressive SEGs, its low per capita energy consumption, low population density, and adequate weather resources limit the direct LULC impacts of SEG-compatible wind and solar PV infrastructure configurations. For regions with higher per capita energy demands, larger populations, and higher population densities, the LULC impacts of SEG-compatible deployments will likely rise dramatically. In regions where energy consumption habits and potential landscape impacts of wind and solar PV infrastructure deployment create friction among stakeholders, well-informed deliberation and cooperation must prevail. Just as climate change is a shared challenge, the landscape is a shared asset and must be treated as such.

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Chapter 4: Examining low carbon energy pathways using an energyshed design approach

Abstract

Energy systems are inherently spatial entities, encompassing infrastructure and land requirements; perspectives of system consumers, owners, operators, and employees; and the distribution of profits, social change, and environmental impacts. The spatial relationships between these social and physical components of the energy system drive its ongoing evolution in response to technological advancements, economic trends, and policy directives. A low carbon energy system transition undertaken in response to climate change will require rapid and substantial changes to all these elements and more. To capture these relationships and inform the design of a low carbon future, we propose the use of energyshed planning. An energyshed is the geographic area that contains the land, infrastructure, people, profits, and environmental impacts connected to final energy consumption. Four distinct scenarios are constructed to illustrate trade-offs along different pathways to a low carbon system. Each pathway strikes a different balance between centralized or decentralized energy systems and corporatized or democratized energy system governance. Finally, an energyshed lens is used to perform an initial assessment of the barriers and opportunities for U.S. states to implement a near-term low carbon transition.

4.1 Introduction

Energy policy at all levels of government is increasingly focused on reducing greenhouse gas (GHG) emissions to mitigate climate change. Most efforts center on energy efficiency improvements and the replacement of fossil fuels with low carbon energy resources. Within replacement strategies, electrification of non-electric energy demand combined with electric grid decarbonization predominate (California State Senate, 2018; Vermont Department of Public Service, 2016; Atlanta, Georgia City Council, 2017). Electrification of transportation, heating, and other currently non-electric energy demands competes with the sunk costs of a fossil fueled energy system that touches all corners of the globe, including a supply chain that stretches from exploration and extraction on one continent, country, or region to transportation, refinement, distribution, and consumption in another. The economies of scale of the current system has sustained low energy prices that are widely distributed throughout the world, while concentrating environmental impacts at the mining, drilling, and fracking sites of supply and transport (Unruh, 2000; Harfoot et al., 2018; Healy et al., 2019).

An energy system transition (EST) away from fossil fuels towards low carbon energy resources, particularly wind and solar photovoltaics (PV), has the potential to reduce the global externalities of greenhouse gases but, in doing so, will create local externalities in regions and communities where the impacts of fossil fuel consumption have not been directly felt. This spatial reallocation of energy consumption impacts has witnessed resistance to renewable energy development in the form of moratoriums, zoning changes, and public protest (Andriano, 2009; Phadke, 2010; Pasqualetti, 2011b). Local impacts of and opposition can be compounded by real or perceived inequities in the ownership, control, and benefits (financial and otherwise) of new energy infrastructure. For example, local property owners may resent local viewshed impacts of utility-scale wind or solar development that benefits distant electricity consumers. We contend that these and other geographic aspects of low carbon ESTs must be front of mind when crafting and implementing energy policies that aim to mitigate climate change in a timely, equitable fashion. Failure to do so could risk perpetuating the inequities generated by existing energy systems, trigger resistance among energy system stakeholders to whom the benefits of a low carbon energy system will not accrue, and slow the implementation of low carbon ESTs as a result.

In this paper, we propose the use of energysheds as a lens for viewing both existing and emerging energy systems to assess the social, economic, and environmental benefits of low carbon ESTs across different geographic scales. We define an energyshed to be the geographic area over which energy is produced, refined, transported, stored, distributed, and consumed. An energy system's energyshed therefore represents the geographic area that contains its constituent infrastructure, energy sources, energy consumers, owners, operators, and profits. A more holistic, spatial view of the energy system can help link the benefits and impacts of low carbon energy system implementation across space and among stakeholders. Energysheds can then be employed by policy makers, regional planners, energy developers, community leaders, and other energy system stakeholders to promote principles of energy democracy and overcome resistance to the necessary energy transition to address climate change.

Section 4.2 of this paper documents existing literature that uses energysheds and synthesizes several literatures influential in the development of the energyshed concept. Section 4.3 introduces and compares four low carbon EST pathways with contrasting decentralization and democratization ambitions. Section 4.4 then assesses the fifty U.S. states for their readiness to implement these low carbon EST pathways.

Section 4.5 summarizes the paper's findings and offers avenues for future follow-up work.

4.2 Background and Literature Review

The energyshed concept as proposed here is influenced by the sociotechnical transitions, energy geography, energy democracy, and related literatures. A sociotechnical regime describes the technological norms and standards developed to fulfill one or more societal functions as influenced by external stakeholders and collaborators including regulators, policy makers, scientists, advocacy groups, and related stakeholders. These transitions occur when sociotechnical regimes evolve through technological advances, changing consumer preferences, macroeconomic trends, new regulatory environments, and related external factors (Geels & Schot, 2007).

Geels and Schott (2007) proposed a three-tiered multi-level perspective for viewing existing sociotechnical regimes and diagnosing the circumstances in which sociotechnical regime changes are set in motion. Such regimes form the middle layer in which much of society exists and interacts (consumers, markets, governments, culture, etc.). The bottom layer is the niche level, which develops and incubates new technologies which have the potential to break into the sociotechnical regime when favorable conditions arise. The top layer represents the sociotechnical landscape which captures decadal trends in the political, economic, and cultural realms. The multi-level perspective contends that pressures applied to the sociotechnical regime by long-term trends in the landscape layer allows niche technologies and ideas to break into and reshape sociotechnical regimes. Energy systems past and present provide excellent examples of sociotechnical regimes. Given their foundational role in adjacent sociotechnical regimes (e.g. food systems, water and wastewater systems, telecommunications, etc.) and industrialized societies more broadly, ESTs have become a distinct area of study in recent years (Araújo, 2014).

ESTs, as a form of sociotechnical transitions, tend to occur in stages in both time and space. ESTs are typically set in motion when a new energy source is discovered or exploited (e.g. oil), accelerate as enabling technologies are developed (e.g. gasoline-powered automobiles) and incumbent technologies (e.g. horse-drawn vehicles) offer inferior energy services, and solidify when the new energy source becomes widely available and affordable (Geels, 2005; Fouquet, 2016;). While low carbon energy sources met 12.8% of global final energy demand in 2017, fossil fuel energy remained dominant by meeting 79.7% of 2017 global final energy demand (Zervos & Adib, 2019). Many industrialized nations, having long since adopted fossil fuels as their predominant energy sources, are enacting new GHG and renewable energy targets, reducing fossil fuel subsidies, and incentivizing the deployment of low carbon energy sources. Simultaneously, many developing and impoverished nations are still in the midst of an energy system transition towards fossil fuels to stimulate economic growth and reduce energy poverty (Sokona et al., 2012; International Energy Agency, 2017; International Energy Agency, 2018). As of 2017, twice as much money is spent on subsidizing fossil fuels as is spent on renewable energy subsidies worldwide (Zervos & Adib, 2019).

The early literature on sociotechnical transitions did not explicitly incorporate spatial components of the systems of study either as a driver of regime change or in analyzing its impacts (Lawhon and Murphy, 2012; Raven et al., 2012; Bridge et al., 2013; K. E. Calvert et al., 2017). Geographers have since developed responses both to sociotechnical transitions in general and to energy system transitions more specifically (Bridge et al., 2013; Hansen and Coenen, 2015). Literature in the latter category has recently coalesced under the banner of *energy geography* or *energy geographies* and these works form the foundation of an energyshed lens (Huber, 2015; K. Calvert, 2016). Energy geography, put simply, is the application of spatial analyses and frameworks to aspects of the energy system, particularly those which span political, social, or ecological boundaries.

Energy geography scholarship takes on many forms and covers a wide variety of subject matters from the physical manifestations of energy resources and infrastructures on the landscape to the geopolitical ramifications of energy system development (Zimmerer, 2011). In this vein, Pasqualetti (2011a) notes that "the mix of geography and energy is so common it escapes casual notice." In reply, K. Calvert (2016) adds that "we take for granted the fact that, when it comes to energy, geography always matters." A geographic perspective applied to the transition mechanisms introduced by Geels and Schot (2007) can help make the hidden and implied spatial relationships among the niche, regime, and landscape layers explicit within the multi-level perspective. Coenen et al. (2012) note that a multi-level perspective "could benefit from dealing with scales, in short that the multi-level perspective also becomes a multi-scalar perspective." Raven et al. (2012) concur, arguing that a spatially-explicit version of the multi-level perspective is necessary to accurately chart the course of a socio-technical transition because "any transition to sustainable development will require interaction between spatially distributed actors, institutions and economic structures that exercise power within and across heterogeneous and uneven spaces of innovation." It is these linkages in space among energy system participants and their centrality in the low-carbon EST planning process which motivate the development of the energyshed lens.

Spatial relationships between energy system stakeholders represent one half of the energy geography puzzle. Relationships between local communities, the landscapes they inhabit, and energy infrastructure impacts are every bit as important to consider when considering a low carbon EST. Contemporary energy systems incur a wide range of direct and indirect impacts on human populations, flora, and fauna (Jones and Pejchar, 2013; Moran et al., 2017). A low carbon energy system is likely to require large-scale deployments of new energy infrastructure that will carry different but still significant landscape impacts (Ingerson, 2013; Hernandez, Hoffacker, Murphy-Mariscal, et al., 2015; Shum, 2017; Thomas and Racherla, 2019). Examples of landscape impacts incurred by renewable energy infrastructure include land use, visual and auditory disruption, air and water quality degradation, and cultural landscape values. Energy infrastructure siting is heavily influenced by community support or opposition which is itself heavily influenced by the real or perceived benefits and impacts of infrastructure siting on themselves and their community (Tsoutsos et al., 2009; Low Choy et al., 2010; Gentry et al., 2010; Walker et al., 2014; Carlisle et al., 2015; Hernandez, Hoffacker, and Field, 2015; Komendantova and Battaglini, 2016).

Absent a command and control system of energy system management and imposition of energy infrastructure on local communities, local opposition to infrastructure siting represents a key determinant of the scope, structure, and speed of low carbon ESTs. A low carbon EST that relies upon large-scale deployments of modular, distributed energy resources like wind turbines and solar photovoltaic (PV) panels will likely result in countless individual siting processes, each with its own environmental impact assessments, community engagement efforts, permitting processes, and infrastructure impact mitigation strategies. If energy system stakeholders and governmental organizations are not prepared to deal with these realities, the pace of low carbon ESTs will likely lag far behind that which is required to effectively mitigate climate change. Any credible low carbon EST implementation plan must therefore consider the spatial relationships between landscapes, communities, and energy infrastructure that underpin community support and opposition.

To this end, the energy democracy literature provides further guidance on implementing a low carbon EST driven by and for the interests of local communities. Definitions of energy democracy vary in specificity and ambition. Typically, the concept captures a range of overlapping principles related to the democratization of energy system access, ownership, decision-making, and benefits, and a bridging of these principles to the wider political and social justice movements (Becker and Naumann, 2017; Burke and Stephens, 2017; Szulecki, 2018; van Veelen and van der Horst, 2018; Hess, 2018). Proponents of energy democracy view the low carbon EST not only as a necessity for averting worst-case climate change scenarios but also as an opportunity to redistribute control from incumbent political, economic, and cultural institutions to local communities and individual citizens (Burke and Stephens, 2017; Stephens, 2019). Energy democracy explicitly links the technological substitution of energy infrastructure, energy-consuming devices and buildings, and payment mechanisms in a low carbon EST to the societal reorganization opportunities that the technical substitutions enable (Stephens, 2019). Simultaneously, energy democracy implicitly highlights the distances, physical or symbolic, between incumbent owners, operators, and beneficiaries of contemporary energy systems and other energy system participants, the communities they live in, and the natural landscapes impacted by energy consumption behaviors. Proponents of energy democracy, in turn, advocate for energy system decentralization in order to bring energy production and consumption closer together (Becker and Naumann, 2017; van Veelen and van der Horst, 2018).

Decentralization in a low carbon EST driven by energy democracy principles entails physical restructuring of existing energy systems and the landscapes they inhabit and administrative devolution to regional or municipal cooperatives (Burke and Stephens, 2017; Szulecki, 2018; van Veelen and van der Horst, 2018; Stephens, 2019). In such a paradigm, profit motives and market competition could give way to more localized, holistic decision making processes that prioritize environmental impact mitigation, equitable energy access, and workers' rights (Burke and Stephens, 2017; Szulecki, 2018). A low carbon EST managed with aspects of energy geographies and energy democracy in mind could result in energy systems that are currently located squarely in the multi-level perspective's sociotechnical regime being supplanted by numerous localized energy systems that could more naturally occupy the niche layer. The extent to which energy systems become fragmented (or remain connected) in a low carbon EST will dictate how energy infrastructures manifest on the landscape and thus where energy consumption impacts will be felt. Similarly, given the strength of vested interests in the sociotechnical regimes of today, conducting a low carbon EST is likely to be a slow, uphill battle in ideal circumstances, with or without redistributing authority to niche-level actors.

The combined literature from ESTs, energy geography, and energy democracy provides fertile ground for interrogating future low carbon energy systems during and after an EST. Energysheds are a relatively young and sparsely employed concept in the literature which has the potential to elegantly unify concepts from each of these three threads. Table 4.1 summarizes definitions found in the literature. Five of the six papers[1] use the term extensively and inform our development of our own energyshed definition. Four of the remaining five papers view energysheds as urban-centric regions, where the energy consumption needs are satisfied by resources and infrastructure spread over the landscape surrounding the city in question. Evarts

[1]Tidwell (2011) uses the term once and is included for completeness given the thin literature on the subject.

(2016) takes a more holistic view, acknowledging the energy consumption of suburban and rural areas alongside urban energy consumption, but retains an urban focus for using energysheds in planning activities. We contend that viewing energy flows as a one-way process out of rural areas and towards urban areas limits the applicability of the energyshed concept and disproportionately prioritizes urban populations over rural populations. An urban-centric conception of energysheds ignores the behaviors of real interconnected societies in which energy, people, goods, waste, pollutants, money, and other materials flow freely across urban and rural divides in all directions. For example, a daily commuter that drives an electric vehicle from a rural town to a city center each day and charges their car at home each night could have their energy consumption omitted from an urban-centric energyshed analysis.

The five papers also contrast strongly in which geographies they incorporate in their analyses. Hughes (2009) applies energysheds solely to electricity systems, uses their physical manifestation on the landscape to determine the energyshed's boundaries, and traces the overlap of the energyshed to stakeholders that control some portion of the energyshed for analysis. Evarts (2016) proposes defining energysheds according to electrical power generation potential versus a desired energy sink (e.g. a neighborhood or a city) rather than with respect to existing energy systems or energy governance entities. The remaining three papers are authored by the same cohort of authors who utilize similar geographical domains for their analyses. McManamay et al. (2017) tie urban electricity use and attendant water withdrawal activities to biodiversity impacts and species extinction pressures. McManamay et al. (2019) forecast urban population growth by 2050 and maps the resulting energy and water demand increases to nearby lands. DeRolph et al. (2019) link present power plant locations and fuel types to urban electricity demand centers to accurately define how a city dweller's electricity consumption translates into regional environmental impacts.

Source	Definition(s)
Hughes 2009	“The energyshed is an organizing idea that helps both to understand the connections between urban form and energy use and to engage regional stakeholders in optimizing energy.”
Tidwell 2011	“The spatial extent of the model is defined both by the Great Lakes watershed as well as the accompanying ‘energyshed’ (the geographic area over which electric power used in the Great Lakes Watershed is produced).”
Evarts 2016	“An energyshed is simply defined as that area in which all power consumed within it is supplied within it.” “The purpose of an energyshed is to provide the functions and structure to harvest and dissipate energy to support life, activity, and productivity throughout the energyshed without polluting the environment above its capacity to assimilate those pollutants.”
McManamay et al. 2017	“. . . a region of transmission structures balancing electricity production at power plants with intense consumption in cities.”
McManamay et al. 2019	“[C]ity energysheds” are defined as “spatially explicit regions of power production, transmission, and substation infrastructure required to meet city electricity demands.” “[T]he spatial extent to which urban consumption create[s] an energy sink relative to source-consumption in the surrounding region”
DeRolph et al. 2019	“[T]he network of power plants and transmission infrastructure required to supply electricity to a given point or zone of consumption (for example, neighborhoods, cities and states) on the electricity grid. Cities, which act as sinks in the electricity grid due to elevated electricity demand in urban areas have extensive and overlapping energysheds.”

Table 4.1: Energyshed definitions found in the literature

Energysheds therefore appear to be quite malleable in the current literature, employed to suit a range of analyses and accommodate a wide range of subject areas. It is clear that the existing literature does not agree on what an energyshed is or is not, nor what it can or cannot be.

The term is itself inspired etymologically and conceptually by watersheds which, as energysheds do for energy, link the physical manifestation of water flows in space to the natural and human systems that rely on and manage them. Watersheds have similarly inspired other sustainability-focused terms and literatures including foodsheds (Kloppenburg et al., 1996; Feagan, 2007), ecological footprint (Wackernagel and Rees, 1997; Wiedmann and Barrett, 2010), and carbon footprint (Wiedmann and Minx, 2007; Kanemoto et al., 2016). Each of these terms links human activities to their environmental impacts and delineates the scope of those impacts in spatial terms.

There is also a related term, 'energyscape,' and an associated, disorganized literature that we have omitted for brevity. Howard et al. (2013) is perhaps the closest match to the energyshed concept and literature themes from the similarly nascent energyscape literature.

Though the literature for energysheds remains embryonic, it has the potential to mature rapidly. Its scholarly heritage is robust and its relevance to contemporary societal struggles is clear. With this background in mind, we now demonstrate the utility of the energyshed lens by applying it to potential low carbon EST pathways for industrialized nations.

4.3 A Comparison of Four Decarbonization Pathways

Future low carbon energy systems will likely take on different forms and be implemented at different speeds from one region or country to the next. The initial energy system conditions, stakeholder priorities, and the availability of technologies, energy sources, and financial resources will collectively determine how low carbon ESTs are implemented, what low carbon energy systems will look like, and who will reap their benefits and pay the costs. Given the diverse set of energy system pathways, stakeholders across the full supply chain – from supplier and consumer to environmental and social impact – face considerable uncertainties and risks. Future energy systems could retain the dispersed geographies and centralized ownership structures that are nearly ubiquitous today, or they could become more localized, decentralized, and democratized. Existing energy stakeholders could see their control over the energy system or their role within it change substantially or vanish altogether.

The scenario planning literature offers tools for navigating both potential future pathways and individual stakeholder responses (Varum & Melo, 2010). Schoemaker (1995) describes scenario planning as an "attempt to capture the richness and range of possibilities, stimulating decision makers to consider changes they would otherwise ignore" with scenarios that "are aimed at challenging the prevailing mindset." Scenario planning is actively employed across public and private sector firms in a variety of contexts (Peterson et al., 2003; Volkery and Ribeiro, 2009; Rickards et al., 2014; Witt et al., 2020). Rather than perform scenario planning to *react* to future energy system changes, we are interested in using scenario planning to *proactively* shape a future low carbon energy system with decentralization and democratization goals in mind. As Tevis (2010) argues in response to Schoemaker (1995), “If our planning methodologies fail to take our ability to create the future into account we will miss those opportunities. We must incorporate into scenario planning some means to account for our ability to create the future.”

The remainder of this work develops four possible outcomes for a low carbon EST with respect to energyshed size and democratization (or lack thereof) in energy systems, each of which is driven by particular decentralization and democratization goals under an overarching goal of decarbonization. The four trajectories themselves are akin to the shared socioeconomic pathways that underpin climate modeling efforts that inform the Intergovernmental Panel on Climate Change’s Assessment Reports (e.g. Riahi et al., 2017). Each of the four outcomes is developed relative to a common initial (status quo) energy system for a developed nation with a mature, interconnected electric grid and significant proportions of energy consumption met with fossil fuel energy sources. The status quo energy system is assumed to consist of energysheds that span large geographic areas and are administered by a small collection of private and public actors that disproportionately allocate profits and externalities. Each of the four outcomes is assumed to include large-scale electrification of energy demand and simultaneous decarbonization of electricity systems.

The four low carbon EST scenarios illustrated in Figure 4.1 represent combinations of centralized or decentralized sociotechnical systems and corporatized or democratized ownership and control. Status Quo Substitution (SQS) represents an approximately business-as-usual future in which the physical and institutional structures of the current system are retained and decarbonization is achieved largely through centrally controlled and managed technological substitutions. SQS is the path of least resistance for achieving decarbonization targets but is insensitive to energy democracy ideals and reinforces large energysheds as the dominant form of energy systems. Despite the familiar trajectory of the SQS pathway, the implementation of low carbon energy resources (and thus climate change impact mitigation) could be quite slow if market forces do not compel action or if governmental interventions are not made. Left unaddressed, widespread local opposition to low carbon energy infrastructure installation could delay decarbonization efforts and further entrench inequities in the current system.

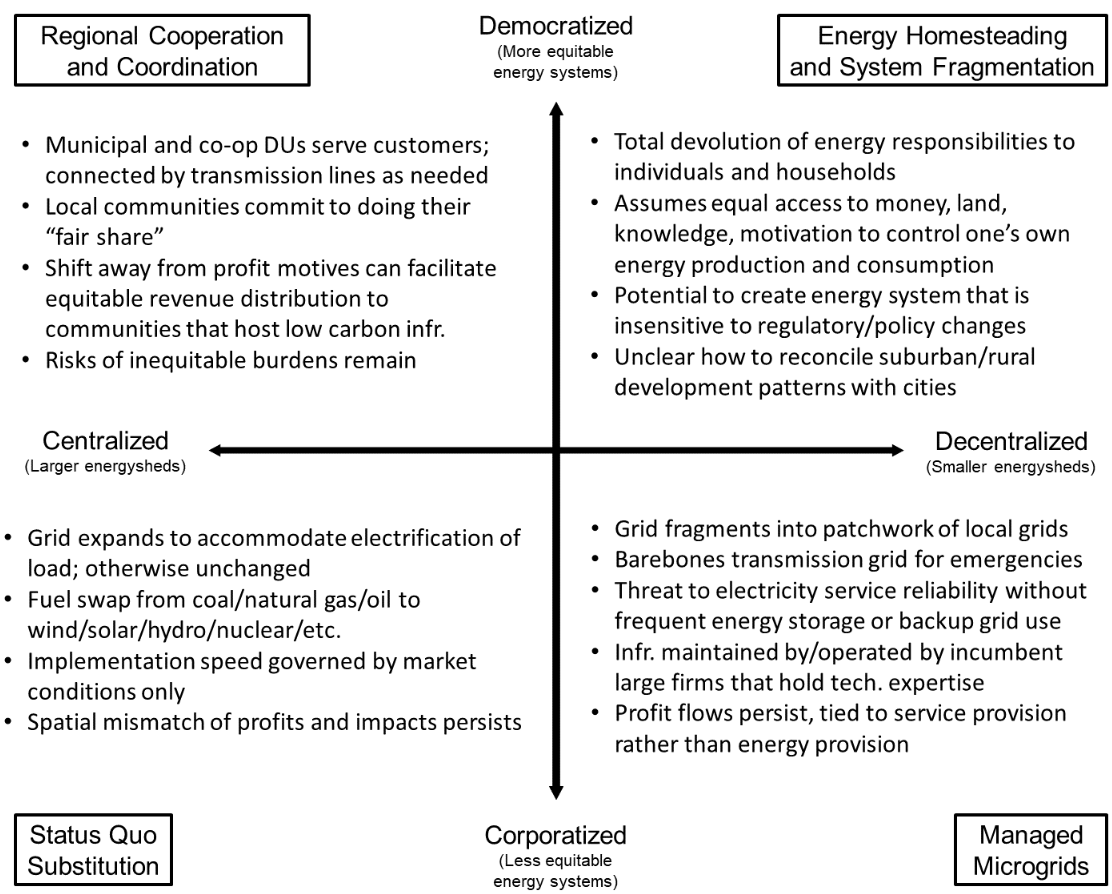

Figure 4.1: Four low carbon EST trajectories viewed through the energyshed lens

The scenario of Regional Coordination and Cooperation (RCC) maintains much of the physical structure of the current system but transitions its administration towards a patchwork of locally-controlled municipal and co-operative organizations.

Implementing an RCC-style low carbon EST would hinge upon local communities stepping up and doing their 'fair share' of low carbon energy infrastructure deployment along with significant financial and administrative reforms within the electricity sector. National or state renewable energy targets would devolve to local and regional planning efforts. Ideally, an RCC electricity system would retain the electricity service reliability and economies of scale that make the SQS system attractive while localizing the revenues generated of new renewable energy investment. Bringing more low carbon energy infrastructure nearer to energy consumers could also reduce transmission infrastructure requirements. Simultaneously, the introduction of local infrastructure installations near previously unaffected communities could engender stronger support for energy efficiency investments as a means of limiting further landscape impacts.

Managed Microgrids (MM) in the bottom right quadrant of Figure 4.1 represents a more ambitious reshaping of the energy system in which the current system is physically fragmented into local microgrids which serve smaller groups of energy customers. A microgrid is typically envisioned as a small, closed system that leverages several small energy sources and energy storage devices to serve electrical loads (Lasseter, 2002). Automated computer control, low carbon energy technologies, energy storage technologies, and related 'smart grid' devices would combine to make microgrid implementation increasingly feasible (Parhizi et al., 2015; Li et al., 2017). Microgrids offer improved short-term resiliency during grid disruptions due to severe weather or equipment failure but, without robust links to neighboring microgrids or a large-scale conventional electric grid, long-term service reliability could suffer. Due to the complexity of operating and maintaining electricity systems, these administrative functions would still be provided by large, centralized, and for-profit firms. An MM energy system could be both costly to implement (over and above the costs of an

SQS-like technical substitution) and deliver only a portion of the localization benefits of RCC.

The final scenario of Energy Homesteading and System Fragmentation (EHSF) represents a low carbon EST pathway in which energy democracy principles guide all aspects of the low carbon EST and energysheds shrink considerably. EHSF extends the physical restructuring of the electric grid in the MM pathway and shifts the development, management, and maintenance responsibilities to local communities and individual homeowners. The status quo would dramatically transform into a patchwork of hyper-local, loosely connected energy systems that, while responsive to local needs and priorities, would dramatically reshape the built environment and social structures. This pathway is only feasible if individual energy consumers (families, businesses, etc.) have the means and the desire to produce and maintain their own energy systems. The EHSF pathway most faithfully delivers the benefits to communities and ecosystems that energy democratization and energyshed contraction. However, the financial, land, time, and knowledge resources required to establish and maintain a self-sufficient energy homestead are not immediately available to most people, particularly those in urban areas who physically do not have the space to install their own production and storage capacity.

These four low carbon EST pathways demonstrate the complexity of modifying energy systems deliberately, rather than purely through the processes described by Geels' multi-level perspective. While each pathway strikes a different balance in fulfilling energy democratization and decentralization ambitions, each reinforces a common theme: given finite resources and limited time horizons to decarbonize the energy system, tradeoffs between implementation speed, ease of implementation, and community support are inevitable. For example, the economies of scale offered by centralized, consolidated energy systems under SQS would likely be severely weakened or eliminated entirely under an extreme version of the EHSF pathway. Total infrastructure requirements to meet energy demands could rise dramatically as the risk of energy generation deficits would drive oversizing of energy generation and storage needs not necessary in unified energy systems. Energy homesteading could also reduce the responsiveness of energy systems and energy system stakeholders to safety and regulatory oversight. EHSF also represents the biggest overhaul of energy systems and societies implied by each pathway, making timely climate change mitigation more challenging.

Alternatively, the extremes of an SQS pathway might meet resistance to the imposition of new energy infrastructure without sharing the benefits to local citizens. Also, the MM and RCC pathways pursue one goal (democratization or decentralization) at the expense of the other. The exact trajectory that is pursued, and thus the manifestation of the future energy system on the landscape, will be determined by the willingness of local communities to accommodate more infrastructure, pay more for their energy, and take ownership of the decision-making process.

As previously discussed, ESTs occur at different rates and follow different trajectories from one region to the next. By constructing some basic metrics for analyzing contemporary energy systems, candidates for implementations of more ambitious pathways can be identified. A rudimentary example of this exercise is presented in the following section.

4.4 An Initial Assessment of Decarbonization Pathway Implementation Potential in the U.S.

The United States presents an intriguing example for studying the potential diversity of a low carbon energy system transition (EST) through an energyshed lens and utilizing the above scenario analysis. There is currently no nationwide low carbon energy target in place in the U.S.; the fifty constituent States have myriad energy and climate change-related policies in place ranging from binding 100% decarbonization mandates to no targets at all. In the absence of federal commitments, many U.S. states and territories have joined sub-national coalitions such as the U.S. Climate Alliance which aims to meet the Paris Agreement GHG targets (United Nations Framework Convention on Climate Change, 2015). The existing U.S. electricity system is itself a patchwork of interconnected grids with nested hierarchies and co-dependencies. America's electricity demand is also met in part by international imports, most notably from Canadian hydropower facilities. These diverse initial conditions are likely to heavily influence if, when, and how a given state undergoes a low carbon EST and which pathway(s) it might follow.

Though states and energy systems frequently do not share the same borders, an initial assessment of each U.S. state's existing energy system can indicate its potential for decentralization and democratization as illustrated above. These assessments will examine the administrative structures of the U.S.' existing electric grids and some basic technical attributes of the generators that power them. Electric grid ownership and operation structures vary from state to state, but are generally comprised of three categories of firms: high-voltage grid operators, distribution utilities, and electricity generators.

Distribution utilities are the entities which own, operate, and maintain local electricity distribution lines, purchase electricity from electricity generators, and collect payments from electricity consumers. In the U.S., they fall into one of three main categories: investor-owned utilities (IOUs), publicly-owned utilities (POUs), and cooperatives (co-ops). IOUs are for-profit, privately held firms that serve the interests of investors. POUs are non-profit firms owned and operated by local or regional governments. Co-ops are privately held, non-profit firms that are jointly owned and controlled by members (i.e. the customers themselves) who share in any profits. IOUs typically operate in higher population density areas where profits are easier to generate thanks to reduced infrastructure costs. Co-ops typically serve predominantly rural areas where IOUs would have difficulty generating profits. The Rural Electrification Act of 1936 and subsequent Electric Cooperative Corporation Act of 1937 paved the way for co-ops to connect otherwise unserved communities to the grid. POUs range in size from small towns and cities with a municipal DU (e.g. Burlington Electric Department serving 20,000 customers in Vermont's largest city) to large metropolitan areas with a unified regional public distribution utility (e.g. Sacramento Municipal Utility District serving 640,000 customers in central California).

To estimate each state's potential to adopt a more democratized energy system, utility ownership scores were calculated per state based on the share of electricity sold[2] by each distributed utility type in 2018. To normalize ownership characteristics along one index, co-op sales were multiplied by 2, POU sales were multiplied by 1, and IOU sales were multiplied by -2. A score of 200 would therefore indicate a state with full co-op coverage and a greater potential for maintaining and expanding energy

[2]Electricity sales were tabulated based on electrical energy (i.e. kilowatt-hours) rather than financial revenues to remove electricity prices as a confounding factor.

democracy principles (i.e. RCC or EHSF pathways in Figure 4.1). A score of -200 would indicate a state with full IOU coverage and a low potential for energy system democratization (i.e. SQS or MM pathways).

Figures 4.2 and 4.3 show each state's utility ownership score compared with their average in-state generator size. Large, centralized electricity generators, including some low carbon energy sources like nuclear energy and large-scale hydroelectric dams, allow for improved economies of scale and cheaper electricity but hinder the ability for local communities to control their local energy production needs. Many low carbon electricity sources, particularly wind turbines and solar PV panels, are smaller and more modular, making local installation and ownership much more feasible. Figure 4.2 reveals that a strong majority of states are majority IOU-served. Only two states, Alaska and North Dakota, are majority co-op served and three states, Nebraska, Tennessee, and Washington, are majority POU-served. Alaska also appears the best equipped to transition towards a democratized and decentralized energy system while West Virginia is in the most difficult position according to these metrics.

Figure 2 also displays generation capacity per capita with colored legend, while Figure 3 depicts the net flow of electricity to or from each state in 2018. Vermont boasts the lowest average generator size of any state but with its relative lack of in-state generation capacity (lowest capacity per capita in the U.S.), it must rely on other states to meet its electricity demands (highest percentage of net imports in the U.S.). In 2018, Vermont had an additional 238 MW of solar PV generation capacity in facilities smaller than 1 MW (Energy Action Network, 2019). These facilities are not captured by the EIA data depicted in Figure 4.2 and because equivalent data are not available for other states, they were omitted. Vermont's population per MW capacity figure drops to approximately 590 people per MW with the distributed solar PV generation capacity included. Vermont could therefore be a prime candidate for

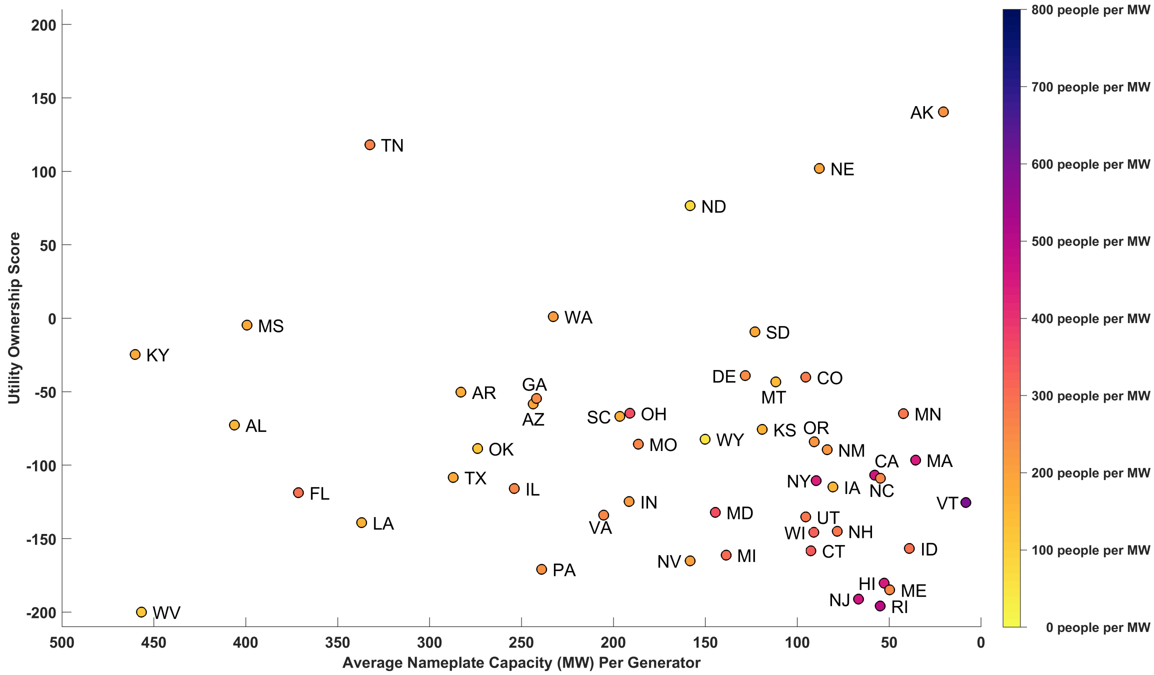

Figure 4.2: State-by-state distribution utility democratization potential scores and average electricity generator size versus total electricity generation capacity per capita

energy system decentralization and energyshed shrinking if it were to install more in-state generation resources.

North Dakota, conversely, is a significant net exporter of electricity while also having relatively strong ownership and generator size metrics. If neighboring states like Minnesota were to meet more of their own electricity needs locally, North Dakota has the potential to begin implementing a more ambitious low carbon EST pathway. This outlook is reinforced when considering the existing penetration of wind and solar PV electricity generation as a share of total in-state generation as shown in Figure 4. North Dakota is ranked fourth in the U.S. at just over 25%, giving it a good head start towards a low carbon EST relative to other states. Wind and solar PV generation in most states is below 10% and some states (e.g. Vermont and California) rely on other states with lower wind and solar PV penetrations to meet some of their electricity consumption. Alaska, which scores well on utility ownership

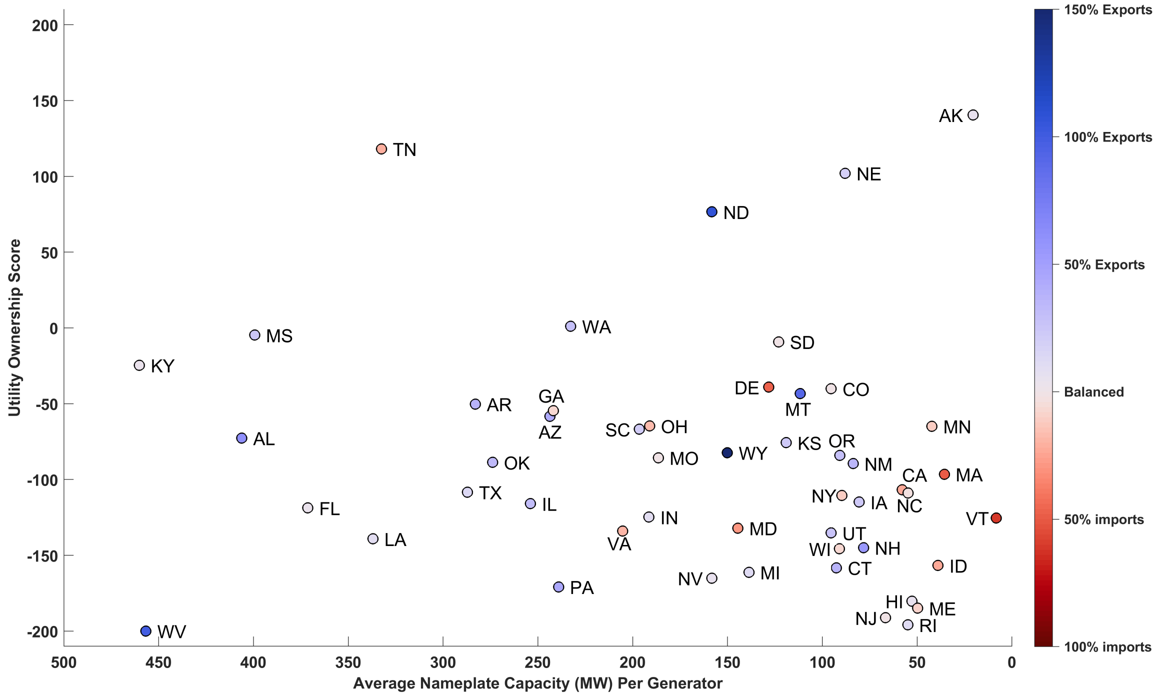

Figure 4.3: State-by-state distribution utility democratization potential scores and average electricity generator size versus annual electricity imports/exports

and generator size metrics, has a limited wind and solar PV generation penetration. Much of Alaska's electricity is generated using local natural gas and diesel generators that serve isolated communities. Alaska is arguably already an example of an MM energy system, albeit one powered largely by fossil fuels. This example reveals more of the underlying complexity in assessing existing energy systems and forecasting pathway implementation opportunities.

This high-level assessment of low carbon ESTs represents a first pass at mapping low carbon EST implementation potential onto real energy systems. In order to more fully capture both the true state of these energy systems and the many factors that will govern their evolution, more focused analysis is needed. For example, an analysis of the New York City metropolitan area energyshed would be difficult to capture using only state-level data. New York City's metropolitan area spans three states (New York, New Jersey, and Connecticut), 23 counties, three grid balancing

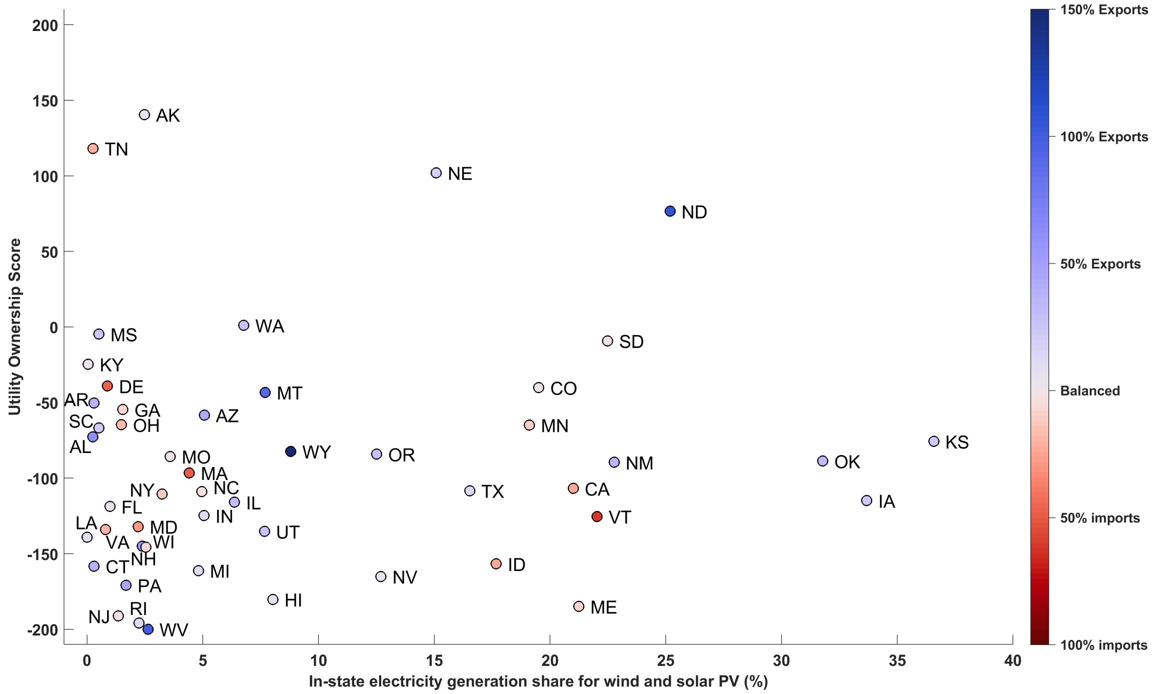

Figure 4.4: State-by-state distribution utility democratization potential scores and wind/solar electricity generation penetration versus annual electricity imports/exports

areas, several distribution utilities of different types, and a wide range of electricity generation resources. Another dynamic that must be considered is the impact of interstate energy relationships as each pursues a different EST pathway (low carbon or otherwise). For example, if Vermont were to more aggressively install new wind and solar PV generation capacity, nearby states and communities that rely on revenues from electricity exports could see their own energy system planning hobbled. By contrast, if states were to collaborate across political boundaries to better harmonize policy making and implementation burden sharing, some low carbon EST pathways could be more quickly and efficiently implemented.

4.5 Summary and Outlook

Given the increasingly urgent need to decarbonize energy systems in light of climate change, new ways of thinking are needed. Energysheds are a relatively new concept with little formal development in the literature, but they have the potential to unlock more effective energy system management that not only accounts for societal and environmental relationships but also centers them in EST management. This paper proposes a unifying energyshed definition based on the combined literatures of sociotechnical and energy system transitions, energy geographies, and energy democracy to help build a foundation for future work in energyshed thinking. Energysheds are then mapped onto a set of low carbon EST pathways to illustrate how different management priorities govern the restructuring of energy systems. Finally, a basic assessment of the potential for U.S. states to adopt different EST pathways is presented. At present, there are no clear-cut leaders in decentralized, democratized energy system implementation in the U.S. but some states are reasonably well-positioned to act accordingly.

This paper only scratches the surface of what energyshed analysis and planning can offer. Future work on the delineating various energyshed scales, with different degrees of cross-border connectivity, could take on many forms and enhance ongoing work in a variety of disciplines. Energy policy studies could use energysheds to reform infrastructure siting processes, electric industry regulations, and financial incentives. Energy democracy advocates could use energysheds to mobilize community participation in ESTs. More technically-focused work in power systems engineering could use the energyshed concept to motivate new transmission planning approaches.

Energy systems as we know them today are both indispensable to societal functioning and increasingly unfit for purpose. With climate change impacts motivating macro-scale action and local-level mitigation burdens stalling these actions, the need for cooperation and collaboration across spatial and political divides has rarely been greater. We must be willing to reshape our planet for ourselves and each other before our planet reshapes it for us.

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Chapter 5: Conclusion

This dissertation approaches the topic of electricity system decarbonization from two directions. The first approach is quantitative and technical in nature, wherein an energy system decarbonization objective is translated into a feasible manifestation of infrastructure on the landscape. The second approach is conceptual, even aspirational, wherein the energy system decarbonization process is recast as not merely a series of technical substitutions but instead as an opportunity to reshape our collective relationships with our planet and with each other. In the former approach, implied spatial relationships between people, landscapes, and energy flows are rendered into precise physical forms. In the latter approach, these physical forms are imagined not only as a means to an end but as a vehicle for wider societal reforms. Taken together, the outcomes of these two approaches point to the same conclusion: though faced with the grave consequences of climate change, we are equipped with the technological tools necessary to combat it and emerge on the other side stronger for it. The only barriers to success that remain are and will be of our own making.

Chapters 2 and 3 contribute to the literature by bridging the gap between electricity system modeling and landscape stewardship. The Vermont case studies presented in these chapters serve as a contribution to local energy system decarbonization endeavors here in Vermont and a platform for future work at a much wider scale. The modeling methods developed in Chapters 2 and 3 show that Vermont's short to medium term statutory energy goals can be met with a variety of different wind and solar PV infrastructure configurations. Each of the infrastructure configurations developed to meet the 12 TWh per year target did so using less than 1% of Vermont's land area. Landscape impacts vary widely from region to region and scenario to scenario, highlighting the need for cooperation across the landscape when implementing infrastructure configurations at these scales. The methods developed to perform the Vermont case study are also applicable to any region of the contiguous United States, enabling more comprehensive assessments of American grid decarbonization options.

Chapter 4 begins where the previous chapters conclude and contributes to the literature by arguing for technological solutions to climate change that are not merely responsive to spatial relationships between humans and nature but are instead driven by them. The low carbon energy system transition now underway in the United States can be far more than a passive process by which energy sources are replaced. The energyshed lens proposed and explored in Chapter 4 highlights how decarbonization can be an active process that not only fulfills decarbonization goals but also delivers more equitable, responsive energy systems in the process. Given the diversity of contemporary energy system administrative structures, energy sources, and geographical constraints, decarbonization is a far from trivial task. Different states and regions will require different solutions and have greater or fewer resources at their disposal. The urgency of climate change, environmental degradation, and societal inequality calls for more cooperative, collaborative solutions to energy system management. Energysheds offer a potentially powerful method for unlocking more ambitious and impactful solutions that acknowledge the spatial and societal relationships that bind us together.

Three predominant conclusions can be drawn from this dissertation and the literature it rests upon. First, electric grids and societies must adapt in unison to both climate change and to intermittent energy sources like wind and solar electricity. The accelerating pace of climate change can be arrested in short and medium time horizons (e.g. years to decades) and reversed in the long term (e.g. the end of this century and beyond) with the implementation of "rapid and far-reaching" societal transitions towards sustainable energy resources. In the absence of an unforeseen 'silver bullet' technological solution, this will inevitably be an uncomfortable and disruptive transition. The business-as-usual alternative to undertaking a low carbon energy system transition would trade human convenience for severe planetary-level disruption and damages. Political leaders, business leaders, and scholars must lean into the task of managing a disruptive energy system transition lest the control of the situation be ceded to Mother Nature's whims. Intermittent, low-carbon energy sources are one imperfect part of the wider suite of options, but they are arguably the best option in hand. Rather than let great be the enemy of good, we must act swiftly and diligently with the tools at our disposal now.

The second outcome of this dissertation is closely related to the first: the trajectory of the low carbon energy system transition is uncertain but controllable. The business-as-usual growth trends of low carbon energy sources are encouraging but insufficient. More worrying, however, is the piecemeal implementation of low carbon energy systems from one city, region, or nation to the next. Climate change is an inherently global challenge and requires a global response. The good news is that we have agency over the problem and can act to change our circumstances. Climate change is not inherently inevitable. We are fortunate to have a thorough understanding of what has caused the problem and many of the tools we need to solve it. These tools include technologies, money, labor, and public policy. The climate change mitigation trajectory we ultimately follow will depend on when, where, and how we leverage these tools.

The third and perhaps most crucial conclusion that this dissertation provides is the fundamental importance of coordination and cooperation to implementing a just and timely low carbon energy system transition. The climate change mitigation tools we have at our disposal are distributed among many different hands around the world, and often inequitably so. Implementing a wind and solar PV infrastructure configuration in Vermont (or any other region) will require concerted, whole-of-society actions; landowners hosting the infrastructure, consumers adapting to potential electricity price fluctuations and service disruptions, governments and utilities adopting new legal and financial structures, and so on. If one party imposes their preferences on the others or ignores the ramifications of their actions, the low carbon transition will bog down in disputes and cynicism. This dissertation's findings both rely upon and highlight the need for the participation of everyone connected to the energy system when undertaking a low carbon energy system transition.

5.1 Avenues for Future Research Activities and Extensions

Several extensions of the work carried out in this dissertation are possible. First, the REGS model can be further enhanced by accommodating additional energy infrastructure types, including rooftop solar PV panels and offshore wind turbines. Rooftop solar PV panels were not implemented in the REGS model for this work as it could significantly complicate the modeling process and dramatically increase computing resource requirements. Comprehensive roof geometry information is not publicly available for Vermont either generally or for buildings with existing rooftop solar PV panel installations. Such a dataset would enable more accurate modeling of rooftop PV electricity generation for both existing and hypothetical new installations. If this capability is developed in the future, a suite of new analyses would be unlocked. Land area requirements of large-scale solar PV configurations could be significantly offset by the adoption of rooftop solar PV panels as opposed to ground-mounted solar PV panels. An inventory of suitable rooftop areas, parking lots, and other developed areas would enable the development of large-scale wind and solar PV infrastructure configurations in the REGS model that could return similar electricity generation returns with substantially smaller land area footprints. Similarly, offshore wind turbine modeling in the REGS model could reduce overall infrastructure requirements by exploiting higher quality wind resources available at sea. Modern offshore wind turbines typically have larger nameplate capacities (up to 12MW at time of writing) and are much taller than onshore wind turbines. Adding this functionality to the REGS model would also better reflect the impending real-world growth of offshore wind turbines in the United States. At time of writing, America has a total of five offshore wind turbines which are located in the Atlantic Ocean hear Block Island, Rhode Island. Several offshore wind energy projects have been approved for installation along the coast of New England, New York, and New Jersey in the coming years. Capturing these low carbon energy sources in future REGS modeling is a clear priority.

A second key potential extension of the REGS model is the inclusion of land parcel geometry and land value information. These datasets were not included in the preceding Vermont case studies because the State of Vermont's parcel data is maintained at the town level and a consolidated, unified dataset is still in the process of being constructed by the State of Vermont at time of writing. For states or regions where such data are already available, the inclusion of land parcel and value data could provide additional siting suitability criteria for modeling activities. Land parcel boundary information in particular could help shape individual infrastructure configurations to more appropriately match eligible plots of land. These improvements could enhance the utility of REGS model outputs to stakeholders by more realistically reflecting the impacts of infrastructure deployments on towns and landowners.

A third, more ambitious extension of the REGS model is the inclusion of energy storage devices, particularly batteries. The REGS model is currently able to compare hourly electricity demand to wind and solar PV generation. Any surpluses and deficits in generation could potentially be translated into energy flows into or out of energy storage devices. Battery storage is not yet a major contributor to electricity supply or demand in North America, but this is likely to change as intermittent generation resources are increasingly relied upon and batteries become steadily cheaper. Studies of battery storage requirements, impacts, and costs are another active area of research and incorporating them into the preceding case studies would have simply been too much to tackle in one dissertation. Nonetheless, they are an important piece of the puzzle and worthy of incorporation in the future.

A final option for future extension of this dissertation is to use the REGS model to construct wind and solar PV infrastructure configurations that comport with the proposed alternative electricity system structures proposed in Chapter 4, figure 4.1. Each of these electric grid configurations implies a particular rearrangement and/or reallocation of wind and solar PV infrastructure in space. For example, a Managed Microgrids pathway could imply the installation of wind and/or solar PV infrastructure on a town by town or county by county basis in Vermont. Each town and county in Vermont has access to different quality wind and sunlight resources. Depending on the infrastructure choices made by each community, their local landscape impacts could be significantly higher or lower than those from a statewide infrastructure solution. In turn, the costs associated with implementing a local low carbon energy system could rise or fall substantially. A unified case study leveraging the methods of all three dissertation chapters could reveal even more impactful results for electricity grid stakeholders in Vermont.

5.2 Connections to Ongoing Events

As I complete this dissertation, two significant landscape level factors are beginning to exert their influence on the implementation of low carbon energy systems. The SARS-CoV-2 pandemic of 2019-2020 has spread worldwide as of April 2020 causing millions of infections and many thousands of deaths. Governmental restrictions on local and international travel, public and private gatherings, and non-essential business activities have been imposed. In turn, economic activity has dropped suddenly and sharply, job losses are growing rapidly, and uncertainty is rampant. The ramifications of the SARS-CoV-2 pandemic are still being created but are certain to be felt for many years to come. Specific to the scope of this dissertation, it is noteworthy that greenhouse gas emissions and energy consumption have both dropped in concert with the decrease in economic activity and travel. Electricity consumption patterns are also in flux thanks to decreased industrial activity, remote working and schooling activities, and the usual seasonal transitions from winter to spring and summer to autumn. More relevant to this work, however, is the capacity for industrialized societies to implement low carbon energy system transitions in the medium-term. The immediate and short term systemic economic shocks will almost certainly impair the ability of governments, businesses, and homeowners to implement otherwise ongoing low carbon energy projects either for economic or physical reasons. Oil prices are also at historic lows, potentially further disincentivizing investments in low carbon energy sources. Future efforts to plan, finance, and implement low carbon energy projects could be significantly delayed or canceled outright. Given the climate change pressures discussed throughout this dissertation, such a delay could prove very costly in terms of climate change mitigation.

Questions about the economic and societal path(s) forward in the wake of the

SARS-CoV-2 pandemic are already being asked by public servants, economists, and scholars. After its initial introduction in the US Congress in early 2019, the Green New Deal has re-emerged as a potential vehicle for resolving the economic damages from the SARS-CoV-2 pandemic and fighting climate change. The Green New Deal is a collection of proposed legislative reforms, economic reforms, infrastructure investments, and related social programs that aim to deliver a decarbonized society in line with the IPCC's "rapid and far-reaching transitions" recommendation. It also aims to deliver on wider societal reforms such as environmental racial, and housing justice. The name and scope of the Green New Deal are inspired by the New Deal of the 1930's which itself was a response to a sudden and economic depression. The methods developed in this dissertation are directly applicable to a large-scale energy system decarbonization program like that proposed within the Green New Deal. Large-scale implementation of wind and solar energy infrastructure, particularly if driven by governmental investments and job guarantees, would require significant planning processes to determine how much infrastructure would be required, where it would be installed, who would own and operate the infrastructure once installed, and how electric grids would be modified to accommodate these new generation resources. The REGS model and energyshed lens introduced in this dissertation could make valuable contributions in each of these areas.

5.3 Final Remarks

The overarching conclusion of this dissertation is that climate change is an eminently human problem: we have caused it and we can solve it if we choose to do so. I hope we choose to do so and that this dissertation makes a meaningful contribution to our climate change mitigation efforts.

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